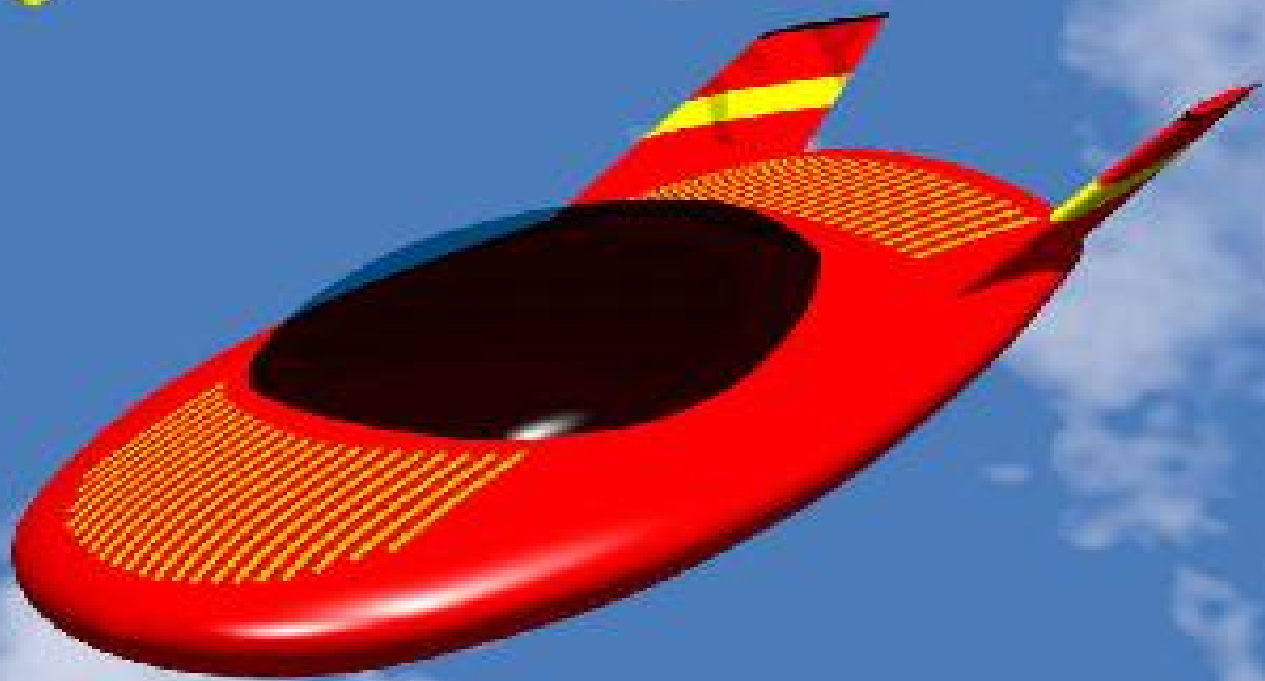


Where Is My Flying Car?



A Memoir of Future Past

by J Storrs Hall

Where is my Flying Car? A Memoir of Future Past

J. Storrs Hall

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Preface

Dallas/Fort Worth Intl (KDFW) is currently experiencing departure delays of 16 minutes to 30 minutes (and increasing) due to taxiway congestion.

How is everybody else affected? View the MiseryMap.

—flightaware.com

I am sitting in the airport in San Francisco, waiting for my flight home. Getting up early was no problem: I've woken up every day this trip before 5:00 AM, which was still 8:00 to my jet-lagged body. So I showered considerably longer than I would like the Sunnyvale Water Authority to know about, luxuriated over a breakfast of rubber sausages and industrial scrambled eggs, checked out, and was on the road by 7:30. It's half an hour to the airport, SFO, if you get there before the rush-hour traffic congeals Highway 101 into a fifty-mile parking lot. The San Jose airport would have been closer to my hotel, but there isn't a flight from there to where I'm going at anything approaching the right time or the right price. Once I got near SFO, I had to refuel my rental car, return it to store, and drag my luggage onto the "airtrain." This is a piece of Disneyfied transport engineering that appears to combine all the disadvantages of buses, trains, and roller coasters in one vehicle. Once at the terminal, one drags the luggage through an interminable labyrinth of hallways, moving pedestrian ways, escalators, elevators, and finally the serpentine line at the airline check-in desk. That took another hour. Another half hour was invested in standing in the queue to experience the only really Twenty-first Century technology of the whole trip: the millimeter-wave radar "see you nude" machine. Various smaller chunks of time have been spent doing things such as the actual check-in process and walking from security to my gate. I've walked over half a mile, dragging my luggage about half of that distance,

across long stretches of tiled floor apparently designed to produce as much noise as possible from a rolling suitcase.

I've been sitting in the gate area for about an hour, variously watching the other passengers, surfing the Web, attempting to write this introduction, and being loudly warned every five minutes that I must not park in the pick-up lanes, and that if I leave my luggage unattended, it will be confiscated or destroyed. It's nearly 11:00, and the plane is about to board. My flight is scheduled to leave in another half hour.

So far, I've been lucky. I haven't had to use the hour cushion I left in my schedule for any unforeseen hitch; but as a general rule it's a very good idea to have such padding in your travel plans.

I'm not the only one with an upholstered schedule. As it turned out on that particular trip, our aircraft arrived late on its previous flight, so we took off half an hour behind schedule. As we approached Newark, NJ (EWR), our destination, weather had backed up air traffic so we were put in a holding pattern, flying in circles over eastern Pennsylvania, for another 20 minutes. But the airline had put so much slack in the timing that we were only 10 minutes late according to its schedule. We spent something over 5 hours in the air with the hold; from gate to gate, including waiting on the tarmac for takeoff and taxiing, it was 6 hours.

Once I landed, there was another hour involved in retrieving checked luggage and getting back to my car, courtesy of another EPCOT-style monorail. From there it is a 3-hour drive back to my eastern Pennsylvania home, directly underneath the circles we were making in the air during the hold.

The whole trip has taken, from door to door, fourteen and a half hours. My net speed, for the 2450 miles from hotel to house, was 169 mph.

The Boeing 737 I flew on has a cruising speed of 514 mph. Imagine that I had had a flying car of my own that could cruise at 500 mph. The trip would have taken less than 5 hours, a third of what it actually took. In fact I could have saved time with a flying car only half as fast as the airliner; since I was up early anyway, I could have left at 5:30 California time (8:30 EST), not flown the hundred miles past my house to New Jersey, and after ten hours in the air, gotten home some 6 hours earlier than I actually did.

If you exclude my somewhat unusual situation—I'm an author, after all, so I live in the archetypal cabin in the woods, far from the madding crowd—

add only an hour and a half at each end of the airliner flight for the huddled masses living within an hour of a major airport. You still have a 9-hour trip, and your flying car is still better at 280 mph.

This is 75-year-old technology. Frank Fuller, Jr. won the Bendix Trophy in 1939 at an average speed of 282.098 mph. Most WWII fighter planes did over 300. In '46 a P-51 took the Bendix at 435.5 mph.

When will I be able to buy a flying car that has those kinds of speeds? The answer depends on just what you consider to be a flying car, and how much you're prepared to pay. You can get a low-end helicopter (used) in the \$50,000 range, which will land on a dime, but it doesn't go much faster than your Toyota on an interstate. Moving to the \$500,000 range you can get nice private planes that will get up into the neighborhood of 200; the recently certificated Cirrus "personal" jet gets you over 300 with a pressurized cabin (flying over the weather) for two million dollars. The problem with the jets and the planes are that they do still have to use airports, or at least landing strips; you get a major increase in choice of places and complete freedom of times as compared with commercial air travel, but it's still nowhere as convenient as a car.

For shorter trips, the car advantage only gets bigger. It takes essentially a full day to fly down to visit my mother in Nashville on a commercial airline even though the actual air time is less than an hour and a half, because the feeder flights only run twice a day! In practice, I usually drive the 13-hour trip, taking two days so as to arrive without being completely exhausted, and taking the opportunity to see a sight or visit a friend along the way. But tacking two days onto each end means that the whole trip may as well be a week-long excursion.

Direct distance, as the crow flies, is 555 nautical miles. At the below-10,000-feet-altitude speed limit of 250 kts (286 mph), that's still less than two and a quarter hours.

If I had a flying car, I could afford to visit my mom once a month instead of once a year.

Fifty years ago, in the mid Sixties, we were sure we would have flying cars by now. Where are they? When will we get them, if ever? Will we get the other things science fiction and the popular technology magazines promised in the Fifties and Sixties: robots, space travel, ray guns, mechanical

educators, weather control, universal libraries, rejuvenation, scientific world government, or limitless atomic power?

Technologically, we as a culture became a lot less adventurous in the past half-century. Thus, to guess what we might have done, one must venture a step or two past the limits of the known possible, and speculate on what might have been discovered or invented. This is a project fraught with epistemological peril.

This book is partly a reminiscence of what the pundits of the early and mid twentieth century—mostly science fiction writers—thought the future would bring; partly an investigation about why, or to what extent, it didn't happen that way, and partly a prognostication about whether it could and under what circumstances it might come to pass after all. Thus it attempts to do something impossible. I am not an aerodynamicist nor a power engineer; not a federal regulator; not a physicist, high energy or low; not an economist, a social psychologist, nor a political scientist. I have never even *seen* an urban planner. And yet I am setting out, in all modesty, to tell you how each of these people has messed up over the past half-century. As I pressed forward with my research, I found I was forced to confront possible explanations that went far afield from considerations of pure technology, and at least to some extent to attempt a general analysis of larger social and political trends that impact it.

I can only make one prediction with perfect confidence: I will get it wrong. And yet the beneficial possibilities of a technologically optimistic future are so vast, the possible upsides so great, that even a minor success here and there will make the whole project worthwhile. I have visited many places and learned many things in the process of researching this book, and have had an enormous amount of fun. I hope you do too.

People who think they know everything are a great annoyance to those of us who do.

—Isaac Asimov

Part I. Profiles of the Past

1 The World of Tomorrow



I read “Tom Swift and his Airplane”; “Tom Swift and his Electric Car” ; “Tom Swift and his Submarine” and I said that’s for me.

—C. L. "Kelly" Johnson

Fifty years ago it was clear that flying cars were in our future. Or at least it was clear to any 10-year-old boy who read the stories of Tom Swift, Jr. His “triphibian atomocar” was held in the air by “repellatron rays” and powered by an “atomic capsule” which could “change atomic energy directly into electricity.”

Tom Swift, Jr., was of course a literary offspring of the original Tom Swift, who was seen having adventures with gadgets like an “electric runabout” and a “photo telephone” just about a century ago. He, in turn, was modeled, in a boy’s-adventure-story way, on Thomas Edison, who was something of a popular hero. In fiction, Edison had taken the War of the Worlds back to the Martians; [\[1\]](#) in reality, he invented the industrial research laboratory, produced a huge swath of the technologies that distinguished the twentieth century from the nineteenth, and had towns (*e.g.* Edison, NJ) named after him by a grateful public.

This was augmented by the regard in which technology itself was held in the public mind; the pioneers of invention and of aviation in particular were quite as popular as the heroes of sport. For 1925, Google N-grams counts essentially the same number of mentions for the Wright brothers, Babe Ruth, and Thomas Edison.

Things to Come

And now for the World of the Airmen and a new start for mankind.

—H. G. Wells, *Things to Come*

The bright future world enabled by technology that formed the background of the 60's space-age zeitgeist had been growing since the turn of the century. It accelerated, rather than being damped, during the Great Depression; perhaps people needed something to cheer them up and take their minds off their troubles. For whatever reason, science fiction flourished. H.G Wells' film *Things to Come*, the classic art-deco exposition of the technological Utopia, appeared in 1935 and did a startlingly good job of predicting the beginnings of WWII and the Blitz. Perhaps aided by the cachet of this apparent foresight, but probably as much by the fact that its iconic designs set the tone for half a century of art deco futuristic style, *Things* formed the starting point for most subsequent popular speculation. The influence of *Things* was followed and extended by the 1939 World's Fair, with its "I have seen the Future" pins and the original Futurama. In fact the phrase "The World of Tomorrow" was coined by Grover Whalen, a principal organizer of the Fair. [\[2\]](#) Futurama featured the Streamline Moderne designs of Norman Bel Geddes and helped cement them in the public mind as what the future would look like.

As an aside, the architectural style is sometimes labeled "Googie," generally by its detractors. This nominally refers to Googie's, a West Hollywood coffeeshop designed in 1949 by a student of Frank Lloyd Wright (who was a great admirer of Bel Geddes). It is more likely a backhanded swipe at the Guggenheim Museum in New York, one of Wright's most famous buildings, designed in swooping Modernist curves. But it's also a sweeping trivialization of Wells' full concept of a completely designed society, of which the architecture would be only one part of a harmoniously integrated whole. Wells saw his task as "to make a practically applicable science out of history and sociology."

To bring the discussion back around to the subject of flying cars, note that the group that is the cadre of the technological elite that forms the enlightened scientific world government in *Things* is the community of airmen who call themselves “*Wings Over the World*.” One of the core concepts in Wells’ world view was that a new level of informed, scientific competence was being demonstrated by the emerging technological professional class. Airmen were far and away the most visible example, matter-of-factly doing what had been considered impossible short decades before. In Wells’ scenario, the airmen formed a cadre of competence that naturally inherited the leadership role after the fall of the self-destructive old order. The young Isaac Asimov, deeply steeped in Wells, followed suit with his *Foundation* of scientists preserving and restoring civilization through the fall of a galactic empire.

If it were necessary to find further evidence of the long shadow cast by H. G. Wells across the landscape of futuristic thought, note that the book of analysis and predictions published in 1972 by Herman Kahn was entitled ... *Things to Come*.

Wells’ notion of the enlightened Utopia of the future included scientific government, i.e. run by a technocratic elite rather than a democracy; extremely aggressive deployment of technology, including eugenics; and a Victorian-style exploratory adventurism that valued results over individual life. (Note that many of his concepts were still current enough in the science fiction noosphere to form the background of *Star Trek*.) It is the villains, not the heroes, of *Things to Come* who are well-to-do people who feel they have enough for a comfortable life, and hold the equivalent of a Precautionary Principle. From Wells’ script: [\[3\]](#)

(The mob, by the by, is as well dressed as any other people in the film. It has the well-groomed look which is universal in the new world. It is not a social conflict we are witnessing. It is not the Haves attacked by the Have-nots; it is the Doers attacked by the Do-nots.)

The Post-war World

The notion of a technologically-driven future that was not merely prosperous but wonderful emerged from science fiction to more-or-less serious analysis during World War II. During the war, any promising technical advance was seized upon and perfected, mass produced, and put to violent use. Compare the bombers that ushered America into the war, the one-man one-bomb sea-level Mitsubishi A6M “Zero” dive-bombers, to the ones that saw us out: the nuclear-armed B29 Superfortress, carrying ten tons of bombs at an altitude of 6 miles. Battleships lost place to aircraft carriers. WWII saw the first use of cruise (V1) and ballistic (V2) missiles. The wartime years saw the invention or major development of jets, radar, helicopters, antibiotics, DDT, portable radios, and computers. The aerospace industry quadrupled in size.

Surely all this science, technology, and production could change the world once the war was over and it was returned to the purpose of improving ordinary lives. The writers of the period largely bought into this notion, which had been the premise of *Things to Come* along with a rapidly-growing genre of imitators. It came to be part of the cluster of ideas under the heading of “the postwar world,” along with speculation about the political shape of that world.

The kind of thinking that blossomed into “the future we were promised” in the 50s and 60s can be seen clearly in a review of two books, *Your World Tomorrow* and *Miracles Ahead: Better Living in the Postwar World*, in the *Saturday Review* in 1944:

Half a dozen books have appeared in the last two years in which this recent technological progress is reviewed. The latest two are before us now. They follow the trend of these predecessors.

Of particular interest to us is the description of transportation:

... Some of the cars will also have wings so that they can transport their three passengers through the air if need be. Of course there will be helicopter flivvers, and of course we shall speed through the air at low

cost in giant airliners, so that we can spend a week-end in London or a vacation in the South Seas or the Himalayas. [\[4\]](#)

Flying cars and helicopter flivvers may not be here, but low-cost giant airliners certainly are. Your author notes with mild amusement that he has both spent a weekend in London and vacationed in the South Seas—the point being that this was in the same category as helicopter flivvers. The authors of these books were reasonably well-grounded in the technology of the day, and many of the predictions have in fact come to pass in the meantime. From the two books in the review, we have:

High-octane gasoline

Factory-built housing

Portable radios

Televisions with screens “the size of a pocket-handkerchief”

Air conditioning

Plastics! and a vast increase in synthetic foods and materials

Electronic controls for cooking

Fluorescent lights

Giant airliners and worldwide vacations

Perhaps the most enduring and popular champion of the “world of tomorrow” throughout the actual postwar period was the avuncular Walt Disney, with offerings ranging from Tomorrowland at the Magic Kingdom to his planned Experimental Prototype Community of Tomorrow, *i.e.* EPCOT. Fittingly, after his death the Disney company built EPCOT as a kind of permanent World’s Fair.

The Cessna Family Car of the Air



Mrs. America Wins Her Wings

Remember, Mrs. America likes to go places and see things. And when she does out, that she can cover 600 miles in a morning, to stop or visit in any one of a dozen cities, she's going to fly. And nothing can stop her.

You, she'll be flying, taking off and landing, as easily as she drives her car, in a few hours after she first steps in a plane. Compared to the hundreds of American women flying solo, hundreds of thousands will fly in the post-war years.

Why? Because it's going to be as easy as driving you to the post-war Cessna Family Car of the Air.

© 1945 CESSNA AIRCRAFT CO.



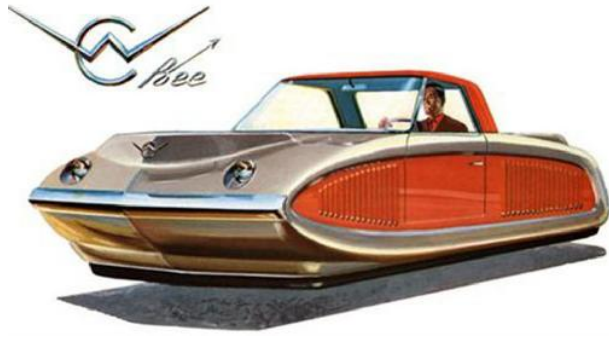
Cessna

SYMBOL OF *Aircraftmanship* FOR THIRTY-ONE YEARS

...

There are similar ads from Piper, Cessna's major competitor of the era, and they continued in this tone well through the post-war tomorrow into the Sixties.

Automakers also got into the act. American cars in the 1950s famously were designed to resemble aircraft, with features such as simulated jet intakes and tailfins. Various experiments were done with cars that actually got off the ground, at least a little bit, such as Ford's Levacar (1959) and the Curtis-Wright Bee:



A Curtiss-Wright marketing concept. They built hovercraft along these lines, but no actual flying vehicle.

The bottom line is that it wasn't just science fiction writers telling us that we would have flying cars. The people we expected to make them, and who themselves expected to make them, told us so as well.

Space Age

Of the 300 covers that graced Galaxy science fiction magazine from 1950 to 1980, only six featured flying cars. More than half were about space travel.

America's romance with aerospace came to a climax in some sense in 1962, the year of John Glenn's orbital flight. Actual events had overtaken the science fiction of the Fifties. Mercury Redstones and Atlases eclipsed Tomorrowland's *TWA Moonliner*.

The Space Age as a phrase and concept had lurked at a very low level in science fiction since the war; in 1952 Random House had added *By Space Ship to the Moon* to its offerings of picture books for children, which had previously consisted of titles such as *Robin Hood*, *Daniel Boone*, *Heidi*, and the like. But the Space Age only lifted off into the public consciousness in 1957 with the appearance of Sputnik.

Besides Glenn and Project Mercury, 1962 saw the launch of Telstar, the first communications satellite, and the publication of Arthur C. Clarke's *Profiles of the Future*. Best-known as one of the top science fiction writers (along with Asimov, Heinlein, and Van Vogt), Clarke was also a top science writer and practicing technologist. As the conceptual inventor of the communications satellite, Clarke was, with the 1962 launch of Telstar, at the top of his game, and his predictions of future technology gained some extra respectability.

Profiles of the Future is an eclectic mixture of takes on future technology ranging from specific existing machines (hovercraft) to informed speculation on possible capabilities based on new physics (antigravity). Some would object to the description of *Profiles* as "serious futurism," noting that there was a history of futurist writing throughout the 20th century, and that particularly in the latter decades there was a rise of "future studies" as an academic field complete with journals and a research literature. Thus we should also consider books such as Herman Kahn's *The Year 2000* (hereinafter *Y2k*); both books garnered over half a million references, according to Google, on the web in 2012.

It's important to note that Clarke wasn't predicting the immediate future. At one point he amusedly notes that people trying to solve the problems of the near term will be disappointed that he seems to be discussing technology that will appear "in the middle of the next century." Indeed, some of his projections are explicitly for the far future. But *Profiles* was by all accounts the definitive take on "the future we were promised" in the minds of serious thinkers, at least those who bought into technological optimism.

Profiles was subtitled *An Inquiry into the Limits of the Possible*, but each progression toward those limits starts out with a look at technologies that could be reasonably foreseen, in general though not in detail, by a technically informed person of 1962.

A measure of Clarke's astuteness can be seen in the precision with which he nailed a technology that is just emerging 50 years after he wrote:

These improvements, however, will be much less important than the fact that the automobile of the day-after-tomorrow will not be driven by its owner, but by itself; indeed, it may one day be a serious offence to drive an automobile on a public highway. I would not care to say how long it will take to introduce completely computerized motoring, but dozens of techniques already developed by airlines and railroads already point the way to it. ...

The *auto*-mobile of the future will really live up to the first half of its name; you need merely tell it your destination—by dialling a code, or perhaps even verbally— and it will travel there by the most efficient route, after first checking with the highway information system for blockages and traffic jams.

The perspective of a science fiction writer surely helped. Isaac Asimov, in a 1964 article about life in 2014, wrote [\[5\]](#) "Much effort will be put into the designing of vehicles with "Robot-brains"—vehicles that can be set for particular destinations and that will then proceed there without interference by the slow reflexes of a human driver." For comparison, Y2k (and other mainstream futurists such as Prehoda) predicts electric cars (along with pneumatic tube trains), but not self-driving ones. Their closest approach is a listing of "automated highways" as a low-probability possibility. In their

defense, this was a perfectly reasonable prediction in 1967. But it was Clarke's genius at inspired guessing just outside the box that makes *Profiles* an enduring classic.

Another clear case in point was Clarke's prediction of world-wide communications networks, where the reality has already overtaken the prognostication:

We could be in instant contact with each other, wherever we may be, where we can contact our friends anywhere on earth, even if we don't know their actual physical location. It will be possible in that age, perhaps only 50 years from now, for a man to conduct his business from Tahiti or Bali just as well as he could from London.... Almost any executive skill, any administrative skill, even any physical skill, could be made independent of distance. I am perfectly serious when I suggest that one day we may have brain surgeons in Edinburgh operating on patients in New Zealand. [\[6\]](#)

Let's have a look at the things that the major technologically savvy SF writers of the day predicted for roughly now; this list is a unification of predictions by Clarke, Asimov, and Heinlein:

Orbital space stations

Lunar landings and bases

Nuclear rockets

Interplanetary travel

Pocket telephones

Home-based videophones (also used for reading and commerce)

"Atomic" power

"Atomic" batteries

Fusion power

Space-based military

Innovative housing technology

Automatic home meal preparation

Major substitution of synthetic food for agriculture

Transportation 1000 mph and one cent per mile

Highways in decline as air vehicles predominate

Self-driving vehicles

Cyborgs

Robots (“will neither be common nor very good in 2014, but they will be in existence.” - Asimov)

Automation eliminating jobs

Wireless energy transmission

Translating machines

Artificial intelligence

Global library

Sea mining

Contraception, revising relations between the sexes

Cures for cancer, the common cold, and tooth decay

Psychology and education a hard science

Some of these have clearly not happened, and some clearly have, but many are in a gray area. The NERVA nuclear rocket engine was built and successfully tested, but never flew and the project was cancelled. [\[7\]](#) (The Air Force even built and tested a nuclear aircraft engine! [\[8\]](#)) The best batteries today are much better than 1962 had to offer, but are still far short of where Clarke (and the others) hoped they would be (able to replace

gasoline in cars). Wireless transmission of energy is similarly advanced but not commercially mature. AI is probably about 80% as far along as they thought it would be by now—but Asimov nailed it about the robots! Sea mining technology is here and it could be a growth industry in the next decades if the legal environment can be worked out. [9] Pocket phones, and the global library in the form of the Internet, are here with a vengeance. As a whole, the science fiction writers were roughly on target, perhaps a decade optimistic on the average, in most fields except transportation and space exploration. It was supposed to be the dawn of the Space Age, and that just didn't happen. The divergence persists with far-future predictions as well: They call for robots in the 2020s, almost certainly correct; bioengineering in the 2030s, very likely conservative; but in transportation they thought we might have interstellar probes, asteroid mining, and gravity control by 2050.

Jetsons

Right at the peak of space-age interest in 1962, Hanna-Barbera introduced *The Jetsons*. From Elroy's "Little Dipper School" to the dog Astro to the name Jetson itself, everything is predicated on the notion that aeronautics and space travel are a big deal in their world of 2062.



The Jetsons' flying-saucer car has become a pop-culture icon.

The Jetsons is perhaps the best-remembered popular exposition of the "future we were promised" of the era. It did a good job of making explicit

many of the ideas about future technology that had seeped into the popular culture from science fiction (and futurism) in previous decades.

The Jetsons in the series are a working-class family bearing the same narrative roles as the Kramdens in *The Honeymooners* and the Flintstones in *The Flintstones*. The first episode is something of a tour de force of caricatured *Popular Mechanics*, post-war-world, predictions. We see flying cars, conveyor-belt sidewalks, powered chairs, large-screen 3D TVs, afternoon outings to Acapulco, Rosey [\[10\]](#) the robot maid, automatic sliding doors everywhere, and Elroy sent to school in a transparent pneumatic tube. Everything (including the windows) is designed in swooping curves, with a style reminiscent of the designs of *Things to Come* or *Futurama*; there are no straight lines in evidence. Everything has antennae or tailfins. Clothing is a cartoon mixture of the neoclassical styles of *Things* and 1950s-era skintight pressure suits.

Jane prepares breakfast by pressing buttons on the Foodarackacycle, a menu-like appliance on the counter. The food appears out of an (automatic, sliding) trapdoor in the kitchen table.

Once George arrives at Spacely Sprockets and his car folds up into a briefcase, he gets from his landing spot into his spacious, windowed office by a moving sidewalk/conveyor belt. He then folds his hands behind his head and puts his feet up on his desk (which is actually an enormous control console festooned with dials, buttons, levers and screens).

It's hard to know where to put the Jetsons in a spectrum from pure fantasy to semi-serious, if firmly tongue in cheek, forecasting. After all, we would never take the Flintstones to give us any idea at all what life was like in the Neolithic, nor Yogi Bear to gain an insight into Yellowstone. They simply used a smorgasbord of woodland and paleontological creatures and phenomena, totally out of context, to lampoon current American suburban life. The Jetsons were much closer to reality, but it's clear that they were also intended to lampoon the *Popular Mechanics*-style world-of-tomorrow optimism, if only gently and hopefully.

I've canvassed a number of people on an informal basis to get a sense of just what they remember as the major differences from the Jetsons' lifestyle to ours. The main answers are the flying car, the hi-rise apartment building with the swooping architecture, and the robot maid. Perhaps it is because the family is so classically stereotypical that no one points out the

pervading subtext: no one does any actual work. Jetson arrives at his office, leans back in his chair, and puts his feet up on the desk. Jane presses three buttons to accomplish the housework—and that's *before* she gets Rosey. Even the robot sets the table for dinner by pressing a button.

——Bottom Line——

Did the Jetsons simply capture the spirit of the space age as reflected in the Apollo program, 50 years of incredible progress in aviation, and the technologically optimistic zeitgeist of the times? I think they did in a subtle subtext that is hidden in plain sight by the nature of the show as a cartoon: the Jetsons' lives are ridiculously easy, and they are ridiculously rich. Jane talks to her mother on a wall-sized videophone in a day when 20% of American households didn't have a television and 25% didn't have telephones. There is a machine in the house that does her fabulous hairdo every morning in a day when a weekly trip to the beauty parlor (complete with iconic beehive hair dryers) was a mark of at least upper middle class status.

Vacations in Europe and Acapulco were the prerogative of the rich and famous—the Jet Set—not day trips for school kids. The working man's family lived in a cramped row house, not a spacious penthouse. His wife didn't have a housemaid; she spent the whole day cleaning, washing, cooking, and sewing. He himself worked long arduous days and was often forced to take public transportation. Private aircraft were a dream almost as far out of reach as they had been before the brothers Wright.

The subtext of *The Jetsons* is simply stated: advancing technology would make the future much better than the past—for everyone. We could *all* be Jet-Setters.

2 The Conquest of the Air

Few people, I fancy, who know the work of Langley, Lilienthal, Pilcher, Maxim, and Chanute, but will be inclined to believe that long before the year a.d. 2000, and very probably before 1950, a successful aeroplane will have soared and come home safe and sound.

—H. G. Wells, *Anticipations* (1902)

The First Age of Flying Cars

The flying machine which will really fly might be evolved by the combined and continuous efforts of mathematicians and mechanics in from one million to ten million years.

—*The New York Times* (Oct. 9, 1903)

The example of the bird does not prove that man can fly. Imagine the proud possessor of the aeroplane darting through the air at a speed of several hundred feet per second. It is the speed alone that sustains him. How is he ever going to stop?

—Simon Newcomb (1901)

Circa 1900, it was the received consensus wisdom of the scientific community that powered, heavier-than-air flying machines were impossible, or, as the *Times* noted, at least a million years off. There were of course no real experts on flying machines, but the scientists that the newspapers liked to quote as authorities on the subject were people like Simon Newcomb, who was an astronomer. I suppose he did have some experience at looking up into the sky. His reputation today rests almost entirely on the various critiques he offered against the possibility of flying machines. As he and the rest of the world were to learn within the decade, his conclusions were wrong; but many of his individual arguments were cogent, although they pointed up problems to be solved, rather than showstoppers to flight.

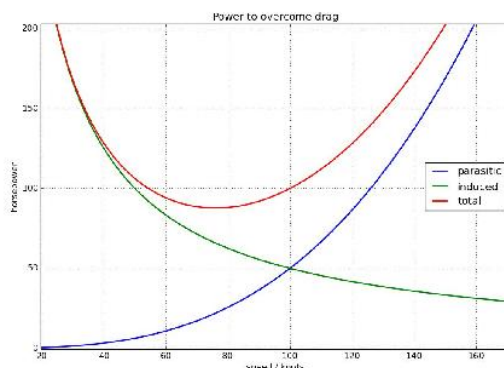
The quoted one is perhaps the most cogent. How does an airplane stop? In fact, we do it by a kludge that is one of the least satisfactory parts of our flying technology: the airplane descends to the ground at flying speed, and only slows down after it is rolling along a lengthy runway. If it were not for this necessity, any airplane would be a perfectly usable flying car.

The Power Curve

The key to flying is energy management. The airplane needs power to stay up (generate lift) and to maintain speed (overcome drag). That power comes from three stores of energy: you have enough energy in your speed to keep flying a few seconds; in your altitude for a few minutes; and in your fuel tank for a few hours. Your takeoff roll tops up your speed in a few seconds; you spend a few minutes climbing to altitude. As long as your engine is working, this is straightforward.

Simon Newcomb had a good point. Indeed the problem is worse than he realized. The problematic part of flying is landing: if you simply point the nose of your airplane downward, you will accelerate alarmingly as your altitude energy is converted to speed, just at the time you wanted to slow down. Thus you take a long, slanting approach trajectory for landing, not unlike takeoff and climb, to let the energy from both altitude and speed bleed off. But even so, you have to be moving at flying speed all the way down, slowing only after you have your wheels on the ground.

Induced drag, associated with the power necessary to create lift, decreases with increasing speed. Parasitic drag, associated with all the other useless stirring up of the air like a boat's wake, increases. Add them together for the total power necessary to fly at a given speed; the resulting graph is called the power curve:



Power curve for a fictitious but not unrealistic small airplane

Intuitively, flying faster than your optimal speed requires more power. Unintuitively, flying *slower* than your optimal speed uses more power, too.

Go to Trafalgar Square and watch the pigeons. To land, they spread their wings wide in a high-lift, high-drag configuration and soar in toward their target spot. Then in the last half-second they flap vigorously. As the pigeon slows down to land, it moves into the left side of the power curve, and uses more power than it would to fly fast. This is the one thing an airplane of classical design cannot do, and not simply because the wings don't flap. The fixed-wing airplane is essentially a glider with a built-in towing system; it isn't possible in general to use the propeller to increase lift without also speeding up. And of course when you're landing you are trying to slow down. But birds, because their method of producing thrust is integrated with the lift, can apply full power, increase lift, and slow down all at the same time. This is why birds can land on branches instead of runways.

The original heyday of the flying car was the 1930s, to an extent that seems to be completely forgotten today. N.A.C.A.'s Charles Zimmerman developed a "Flying Pancake"—a low aspect-ratio flying wing—in the 30s. [11] It is mostly remembered today for being investigated by the Navy for aircraft carrier use during WWII. But Zimmerman's 1932 study [12] begins:

In recent years there has been an increasing demand for an airplane suited to the needs of the private owner. Without going into a discussion of the problem it may be said that such an airplane should be capable of descending along a steep path at such a low rate of speed that it will be unnecessary for the pilot to alter the direction of the flight path or the speed when near the ground in order to make a satisfactory landing.



Zimmerman's Flying Pancake (the Vought V-173).

An airplane suited to the needs of the private owner. The obvious implication was that not only will the airplane be privately owned, but the runway. The runway at the small county airport near my home is a full 12 acres of concrete; the airport as a whole is 100. This isn't going to fit on your suburban lot, or even your country estate. Zimmerman was attempting to design a plane that could emulate the pigeon.



W. R. Custer and his Channel Wing.

There are various examples in aviation history of attempts to do the same thing, or at least approach it. The Custer Channel Wing aircraft, for example, illustrates a technique called “upper-surface blowing.” Custer had patented his Channel Wing in 1929, although it didn't fly until the 40s. The pictured plane, the CCW5, is reasonably close to the specs of the aircar we would like to have. It seated 5, weighed two and a half tons, and cruised at 200 mph. It could also fly at 35 mph, and had a 250 foot takeoff roll. [\[13\]](#) It achieved its low-speed lift by positioning the props so that the intake caused a high-speed airflow over the upper surface (but not the lower surface) of the semicircular wing section.

The main problem with the CCW, which also afflicted the Flying Pancake, was that you had to tilt the entire vehicle to an extremely high angle of attack to get the low-and-slow characteristics. (Note that the pigeon does the same.) This was not only a bit more like a carnival ride than your average passenger bargained for, but obscured visibility of the ground just when it was needed most.

The pigeon, the Pancake, and the Custer all use a lot of power when flying slowly, just as the power curve demands. But at the same time, the landing

aircraft is trying to get rid of excess energy in the form of altitude and speed! What if we could use this energy for the power we need to fly slowly?

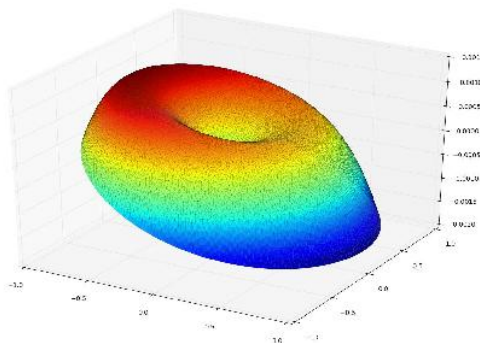
Autogyro

That's the kind of plane for you and me, Ernie, one that comes straight down and slow!

—companion to Ernie Pyle in a PCA-2

Juan de la Cierva was one of the great early aviation pioneers. He had built Spain's first airplane, but then one of his early models stalled due to moving too slowly and crashed. La Cierva set himself to find an improved design. He reasoned that if he could make the wings move fast even when the craft itself was moving slowly, he might solve the stall problem.

In the early 20s, La Cierva invented the autogyro (his commercial name was "Autogiro"), which used what we would now call a set of rotor blades for a wing. The rotor isn't powered; it is in fact a rotary wing. Because it rotates, the speed of the blades through the air can be higher than that of the overall craft, but the dynamics are those of an airplane rather than a helicopter: the wings create lift but cause drag; there must be a separate propeller to provide thrust to overcome the drag. There is no motor attached to the rotor. In simplest terms, the wind passing through the rotor disc causes the rotors to turn ("autorotate"), just as it would a windmill. Each rotor blade is essentially gliding "down" into the oncoming wind.



Torque distribution on an autorotating rotor (turning counterclockwise as seen from above). Red (above 0) is the region where the oncoming wind provides net energy to the rotor and it acts as a windmill. The hole is the region where the blade is moving backward through the air due to the motion of the vehicle.

There were several innovations necessary to produce a working autogyro. The first problem was dissymmetry of lift: rotors on one side, where they are going in the same direction as the aircraft (“advancing”), produce a lot more lift than the ones on the other, where they are going backwards (“retreating”). The resulting imbalance tends to make the aircraft flip over. La Cierva solved this in a typically ingenious way: he put in a hinge that allowed the blade to flap up and down as it went around. This is far from obvious: there is no reason why a blade being elevated would cause it to produce less lift. The solution is subtle. It is not the fact that the advancing blades are higher, but the fact that they are rising, that causes them to see the incoming air at a lower angle of attack, and reduces their lift. Similarly, of course, the retreating (and falling) blades see a higher angle of attack and produce more lift. It’s perhaps more intuitive if you think of a bird, whose wings produce less lift when going up than when going down.

There is another reason a flapping hinge is counterintuitive: how can a wing free to flap upward hold up the airplane? At least the answer here is a bit more obvious: centrifugal force holds it outward.

We are privileged to understand many of La Cierva’s thought processes as he successfully solves the challenges of the autogyro, because he explains them in his very readable autobiography, *Wings of Tomorrow*. He also speculates that a workable helicopter may never be built, not realizing that he himself is solving most of the problems standing in its way.



A Cierva C-30 Autogiro

It is a point of interest not at all unrelated to our story to note that it took most of the 1920s to develop the Autogiro into a useful and reliable form. La Cierva was a legitimate and recognized aeronautical genius but could develop blind spots when his intuitions failed to match the actuality in some detail. One such detail was the necessity of lead-lag hinges in the hub to allow for the acceleration and deceleration of the blades as they went around. La Cierva argued with test pilot Frank Courtney that there were no aerodynamic forces to make the blades do that. Courtney won the argument when two blades broke off an Autogiro he was flying in 1927 due to metal fatigue (luckily he survived). [\[14\]](#) Ironically, the acceleration is due to the flapping hinges, La Cierva's signature invention. Flapping causes the blades to emulate a twirling skater's arms, in and out every turn. But it is very often the man in the machine, not the one in the office, who notices such problems with the urgency they deserve.

La Cierva refined the Autogiro through the 1920s, making and selling them in England. In 1929 he was visited by American aviation pioneer Harold Pitcairn, who had built the successful aircraft company which ultimately became Eastern Airlines. Pitcairn was quite taken with the Autogiro, bought the rights to build and develop it in the USA, and cross-licensed and collaborated with La Cierva in its further development. In 1931, a Pitcairn Autogiro landed on the White House lawn, as part of the ceremony in which President Hoover presented Pitcairn with the Collier Trophy for outstanding achievement in aviation. The same year, Amelia Earhart made a transcontinental flight and set an altitude record in an Autogiro; she

published an article in *Cosmopolitan* in August saying that soon “country houses would have wind cones flying from their roofs to guide guests to the front lawn landing area.” [\[15\]](#)

Autogyros captured the public interest in the 1930s; in fiction, everyone from W. C. Fields to Doc Savage flew one. The groom arrives at the wedding, landing on the lawn, in an autogyro in *It Happened One Night* (1934). There was a autogyro-like craft featured in *Things to Come*, in 1935, in a Norman Bel Geddes Streamline Moderne style. Heinlein’s flying car as described in *For Us, the Living* (1938) is quite similar. This was before the need for a side-facing tail rotor in a powered-rotor helicopter was understood, so the fictional designs looked like the (working) autogyros of the day, with thrust propellers.

The gyros of the early Thirties had wings, but the ones of the later Thirties did not. The difference was what was called the “direct control” rotor hub, invented by La Cierva and incorporated on the C-30 and most later Cierva and Pitcairn models. This meant that the pilot had a direct handle on the cyclic pitch of the rotor, rather than influencing it by way of the attitude of the fuselage (as by ailerons on wings).

In 1936, in one of the ironically tragic knife twists of history, Juan de la Cierva was killed when a conventional commercial airliner (a DC-2) crashed on takeoff in Croyden, England on his way back to Spain. Besides the personal tragedy, this was a disaster for the autogyro community at large. La Cierva had been not only its intellectual but to a large extent its spiritual leader. After his death, one can sense in the historical record a breakdown in the friendly rivalries among the various inventors, engineers, and entrepreneurs, and the rise of serious antipathies.

The English company La Cierva had founded quit autogyro work to focus on helicopters, refusing to share technical information with Pitcairn, even though contractually obligated to do so. Somewhat inexplicably, given the looming hostilities of WWII, they licensed their technology to Focke-Wulf, which flew the first practical helicopter, the FW 61, in 1936. German submarines carried the Focke-Achgelis FA-330, a towed observation gyrocopter on a 400-foot tether, during the war.

Back in the US, Pitcairn continued with refinements of the Autogiro, going through some 36 models over the decade. Ultimately La Cierva and Pitcairn invented almost everything that goes into a working helicopter.



The Pitcairn AC-35 roadable autogyro on the streets of DC (National Air & Space Museum).

If it hadn't been for the Great Depression and then WWII, the autogyro might well have gone on to be the basis for a widely used flying car. Its STOVL (short takeoff, vertical landing) capabilities made it amenable to landing on and taking off from driveways or parking lots. The AC-35 could fold its rotors, drive on the streets, and park in an ordinary garage. And it had in Pitcairn an experienced, competent, well-funded sponsor who was specifically committed to the goal of private flying machines.

Historically, the name "Autogyro" was used by La Cierva and Pitcairn from the 1920s as a trademark. "Autogyro or gyroplane" was used by Glauert in 1926 in his classic analysis, evidence that both words were already in use to describe the general type. "Gyrocopter" is a more modern usage (and also a trademark), and "gyroplane" is the standard FAA designation.

Gyroplanes are safer, in one regard, than either fixed-wing aircraft or helicopters, because they can land on a dime with the engine out, and indeed the engine can fail at any time, even on takeoff, and the craft can float to a landing. Over either mountains or cities, this is a distinct advantage because a nice long flat place to land is hard to find! In practice, however, they have tended to have a high accident rate. Part of the reason is that today, most gyroplanes are homebuilt ultralights piloted (even designed!) by their builders without much training in the type. A pilot who has trained in a fixed-wing airplane is taught, by precept and continual practice, to get out of trouble by pushing the nose down to avoid a stall. But

in a gyroplane, this is exactly the wrong thing to do. Pushing the nose down can cause the rotor to lose autorotation, and thus lift, with no way to restart it. Even worse is a design with the propeller thrust line above the center of gravity, which will tend to cause the same behavior.

Properly designed gyroplanes with properly trained pilots, however, have a number of advantages, starting with low takeoff and landing speeds and thus short runways. They are also less susceptible to wind than airplanes, perhaps surprisingly: the high speed of the rotor makes the wind speed a smaller factor by comparison. The gyroplane also has some safety advantages over the helicopter; the helicopter can be shifted into autorotation in the case of an engine failure, but there are parts of the flight envelope where this is impossible to pull off in time. The autogyro is already in autorotation: in one of its very earliest flights, La Cierva's first working autogyro, the C.4, suffered an engine failure on takeoff at about 30 feet altitude, and simply settled to a safe landing. Furthermore, the helicopter has an obscure failure mode that can happen in hover or slow descent, in which a vortex ring forms around the rotor disc and causes the blades to do the equivalent of a tire spinning on ice. You start going down, your instinct is to apply more power, but that just makes it worse and you lose even more traction. It's a lot like stalling an airplane in that respect. This can't happen with an autogyro, basically because it can't hover in the first place.

Takeoff in a gyro is more difficult than in a fixed-wing airplane, but landing is easier. The ratio of takeoff to landing gyro accidents in the 30s bears this out (as does your author's personal experience). The most common accident in a plane is slipping, stalling, and crashing on approach. In a gyro, it is tipping on takeoff with a rotor ground strike. You are much more likely to walk away from rotor strike than an approach crash. In 1932 *Fortune* magazine carried an article that listed the ten worst autogyro accidents to that time — none of them fatal.

Gyroplanes didn't catch on as a segment of aviation for a number of reasons. The first and most obvious is that they were superseded by helicopters. A gyroplane is in practice a compromise between an airplane and a helicopter; one manufacturer advertises that it "does 90% of the mission at 10% of the cost." It's probably fair to say two thirds of the mission at one third the cost. In today's specialized commercial market it

loses to the extreme cases for particular applications: airplanes for speed and fuel efficiency; helicopters for hovering and vertical takeoff. The advantages of the compromise were, in Zimmerman's words, "an airplane suited to the needs of the private owner." A private car is likewise a study in good-enough trade-offs.

Convertible airplanes

The flying cars in Heinlein's 1951 *Puppet Masters* are essentially convertible STOVL (short take-off, vertical landing) airplanes. Reading between the lines, they generally fly from "takeoff platforms" but can be operated from "a street wide enough for an illegal takeoff" in a pinch. "Wide enough" instead of "long enough" indicates that Heinlein was thinking about wings. There are "landing plots" that feed into the roads but the cars can put down in any clear area if necessary. They appear to carry RATO (rocket assisted takeoff) units, which would allow a takeoff, albeit a noisy one, from a very short field. H. Beam Piper's aircars in the 1958 story *Lone Star Planet* are quite similar. This gives some credence to the idea of an informal consensus in the Fifties among the SF writers who were most savvy about current technology and keenly interested in near-term developments.

In the early days of the postwar world, it did indeed seem as if the Cessna Family Car of the Air would take off. Due to some federal pilot-training and training-aid programs, licensed pilots in the US increased from 50,000 in 1940 to 350,000 in 1950. (It should be noted that both Germany and Japan had just been reduced to smoking ruins by saturation bombing, and that the only existing defense against such an attack was to put a huge cloud of fighter planes in the air to shoot down the bombers.) In 1946, a record 35,000 general aviation planes were sold. [\[16\]](#)

Why then can't we simply consider a private plane to be a flying car? The obvious answer is that it's not a car. You have to drive to an airport to fly it, and leave it at the airport where you land, and get another car there to go to your final destination—the "three vehicles problem." It will be worth considering private airplanes as a possible lead-in path to flying cars later, but our present task is to consider the feasibility of a full-fledged car replacement: something you get into in your own garage or driveway, and get out of at your final destination.

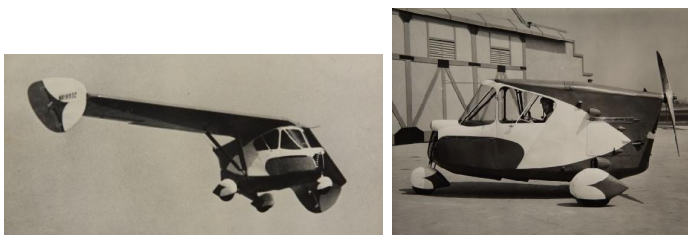


The Dymaxion Car in 1933. (Sascha Pohflepp / Wikimedia (CC))

The most famous attempt at a convertible car/airplane in the early 1930s was Buckminster Fuller's Dymaxion Car. Its elongated egg shape was much more aerodynamic than cars of the day; it had a three-wheel stance, steered by its single rear wheel, as was standard for airplanes then. Fifty years later, Fuller explained the idea:

When what we call a light plane, one flown by an individual, lands crosswind, its fairing or streamlining makes it want to turn violently in the direction of the wind—the direction of least resistance. This is called ground looping. I realized that the most difficult conditions for my omni-medium jet-stilt superbly faired flying device would be when it was on the ground. What is popularly called the Dymaxion Car were the first three vehicles designed to test ground taxiing under transverse wind conditions.

The Dymaxion did indeed inherit this problem from airplanes and was considerably less stable on the ground than ordinary cars. It also had the problem that it would tend to lose contact with the ground at high speeds, purely due to its shape; it never had any wings attached. Needless to say it never flew.



The Waterman Aerobile in flight and on the ground. (San Diego Air & Space Museum)

The first fully functional fixed-wing flying car was Waldo Waterman's 1937 Aerobile. Waterman in 1932 had built and flown the world's first tailless ("flying wing") airplane. This was incidentally also the first plane with modern-arrangement tricycle landing gear, with two wheels in the back and a steerable nose wheel. This is considerably more stable and resistant to ground-looping in a crosswind than the old "tail-dragger" configuration. The Arrowbile was by all accounts relatively easy to fly. The wings could be removed, and the fuselage part driven around as a car. Five were built; unfortunately, on top of the difficulty of trying to sell them into the Great Depression, Waterman's financial supporter and promoter died unexpectedly, Waterman himself had a serious illness for a year, and then like almost every other major aviation figure was swept up in the WWII military aviation surge.

For the Duration

Doc [Smith] could do almost anything and do it quickly and well. In this case he was selecting and road-testing for me a secondhand car. After rejecting numberless other cars, he approved this one; I bought it. Note the date: August 1940. We entered World War Two the following year and quit making automobiles. I drove that car for twelve years.

—Robert Heinlein

The first great age of flying cars was the 30s; despite being damped by the Great Depression, the technology advanced considerably over the period and might very well have produced a landscape of aviation considerably different from the one we actually got. What really clobbered the first age of flying cars was World War II.

Private aviation essentially vanished for the duration. Besides Waterman (who would end up teaching pilots), pilot and aeronautical engineer Moulton Taylor worked for the Navy's missile program, and Ted Hall, who had experimented with similar modular designs, wound up working on the PBY Catalina and the B-25.

The Navy seized Pitcairn Aviation's airfield in 1942 under threat of eminent domain, paying him a third of its value. Pitcairn had developed the technology that made helicopters possible: this was such common knowledge in the aeronautical engineering world that the key patent was referred to simply as "582." But in a patriotic gesture Pitcairn substantially reduced royalties for any of the several new helicopter companies—Sikorsky, Piasecki (Vertol), Bell—that were building helicopters under government contract. Under the terms of his agreement, the waiver expired in 1946. With the prospects of having to pay full royalties, the helicopter companies told the government that the price of helicopters would go up, so the government essentially nationalized the patents. Pitcairn sued. The suits went all the way to the Supreme Court, and ran from 1948 to 1977, by which time Pitcairn himself had been dead 17 years. He was legally

vindicated in the end, the Court finding that the government had infringed 59 claims in 11 separate patents, and awarding his estate damages of \$32 million. But Harold Pitcairn's (and Juan de la Cierva's) dream of safe, low and slow aircraft for general private use had been crushed.



A model of a fully articulated hub constructed by Pitcairn's company as an exhibit in the patent litigation. Courtesy of the Harold F. Pitcairn Wings of Freedom Museum.

The Postwar World

By 1949, Moulton Taylor, back in business, had designed and built the flying car for the postwar world. Taylor's "Aerocar" was a 2-seater coupe with a 143-horsepower engine that made it quite sporty on the road. It had a trailer that unfolded into wings and a tail. They could be attached to the car in about 10 minutes, forming a small private airplane that by all accounts was quite well-designed, stable, and easy to fly. Four of the first model Aerocar were built; one Aerocar II, an improved design, was built, and one of the model I's was rebuilt into a third design as Aerocar III.

Although the Aerocar had more parts that had to be attached than the Arrowbile, namely the tail section, it had the advantage that tail and wings folded up into a trailer that the car part could tow, making the whole business roadable.



Moulton Taylor's Aerocar (NASM)

The Aerocar finally got federal aircraft certification in 1956 — unfortunately, just as the postwar piloting boom had turned into a bust. Together, all the models flew a total of 9000 hours. The (Boeing) Museum of Flight, which now owns the Aerocar III, lists it as having a cruise speed of 135 mph. This would have been extremely useful for traveling in a world where the Interstate highways had not yet been built. The Aerocar solved the problem of needing three vehicles to complete a trip, and made the middle, flying, segment quite a bit faster.

Are we going to be stuck with the 55-mile-per-hour speed limit forevermore? Is this the fastest we will ever go?

—Moulton Taylor

You can take it with you

The other way of finessing the “three-vehicles problem” is simply to have a plane big enough to take your ordinary car with you. This was first accomplished in 1933, as reported in the May issue of Popular Science. It is eminently practical today, especially since modern technology admits of cars that are much lighter than formerly. The pressure towards more fuel economy has resulted in cars that are both lighter and smaller. The problem, of course, is that carrying a car in a plane makes the plane have to be much

bigger, with a heavier payload, than if it only had to carry you and your luggage.

There's one obvious advantage of such a scheme over most of the other ones considered here, though: a plane designed for this use would be perfectly useful for carrying other cargo instead; it would be the aero version of a medium truck.



Ted Hall's ConvAirCar. (San Diego Air & Space Museum)

A variant on the idea is to build an airplane that is specifically designed to latch onto a car and carry it, but isn't capable of flying by itself (it doesn't have a separate cockpit or landing gear). This design, by Theodore Hall, the ConvAirCar, was explored, built, and flown at Convair in the late Forties. Hall himself had been building and flying earlier attempts and prototypes before the war; he was another of the aero engineers swept up in the war effort. Convair put extensive resources into the ConvAirCar. The car part was custom-designed by Norman Bel Geddes student Henry Dreyfuss to match the airplane part. Because of that, the whole machine was fairly close to standard private plane specifications: it weighed about 1500 pounds, carried 1000 more as payload and fuel, had a 190 HP aero motor, and did 125 mph in the air. Its major compromise was in ground mode; the separate car motor was only 25 HP.

The ConvAirCar very nearly succeeded. It was built by a major aircraft company (Convair). They had an ingenious marketing plan: they would sell you the car part, and have a chain of dealers at airports who would rent you the airplane part. When you bought the car part, you had a working car, whether you ever flew or not.

Unfortunately, test pilot Reuben Snodgrass watched the wrong fuel gauge in the air, ran out of gas in the airplane part, and crash-landed the prototype.

Although he walked away from the accident, the resulting news photos of the smashed-up carplane caused so much negative publicity that Convair pulled out of the project, and Hall wasn't able to find another backer.

VTOL

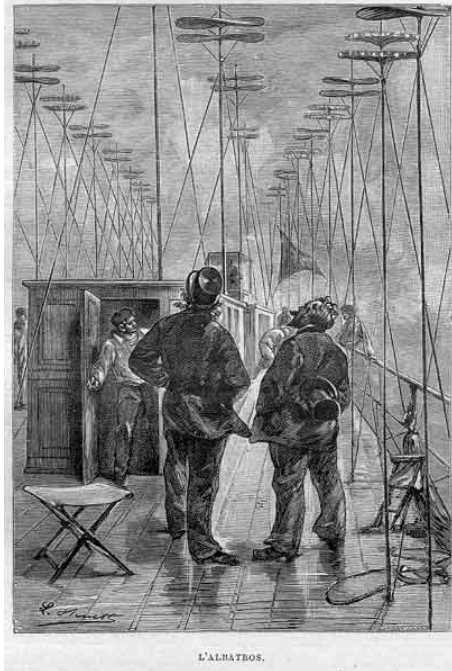
These airplanes we have today are no more than a perfection of a toy made of paper children use to play with. My opinion is we should search for a completely different flying machine, based on other flying principles. I consider the aircraft of the future, that which will take off vertically, fly as usual and land vertically.

—Henri Coandă

They climbed into the car, and the driver lifted straight up to two thousand feet and turned, soaring down to land on the Chief's Headquarters Building, a mile away.

—H. Beam Piper, *Time Crime*

Perhaps the first depiction of a VTOL (Vertical Take-Off and Landing) flying machine in science fiction was at the same time one of the first depictions of a (more-or-less workable) heavier-than-air flying machine of any kind, namely the Albatross in Jules Verne's *Robur the Conqueror*, published in 1886. It is a ship-like vehicle that is kept aloft by the direct thrust of a large number of airscrews:



It's interesting to note that this illustration, and Verne's verbal description, depicts counter-rotating props.

Could we build an Albatross today and would it work? The answer is yes, although it might need a light, aerodynamically-shaped body instead of an open-decked wooden ship! In the years since 1886, a remarkable number of aircraft have been flown that use downward-pointing propellers for lift.

Helicopters

Although helicopters in various experimental forms (and the word "helicopter") had been around from the turn of the century, it was not developed into a practical machine until about 1940. When it was, it used many of the innovations that had allowed the autogyro to work, notably flapping hinges, damped lead-lag hinges, and collective and cyclic pitch controls.

Sikorsky's first working helicopter had three tail rotors: a side-facing one to counteract engine torque on the main rotor and control yaw, and two outrigger ones to control pitch and roll, under a main rotor hub that was essentially like La Cierva's 1929 one. Under prodding from his Army sponsor, he adopted Pitcairn's fully articulated hub using patent "582" and

ten other rotorcraft patents at Pitcairn's low wartime rates. This allowed him to dispense with the two up-and-down tail rotors, leaving only the sideways one in the standard helicopter configuration we are used to today.

The helicopter formed one of the cornerstone ideas of the "postwar world" vision.



The main reason the helicopter didn't catch on to the expected extent is cost. One of the main components of the cost is the rotor hub, which even now is out near the edges of the envelope of technical capability. The hub is extremely complex; it has to be extremely precise—tiny fractions of a degree or millimeters of position matter—and it is under tremendous stress: the blades pull outward with literally tens of tons of centrifugal force. Imagine trying to build a mechanical clock that had to be accurate to a second a day, small and light enough to carry in a suitcase, but which would have railroad cars attached as the hour and minute hands. So the rotor hub is not only expensive to manufacture, but for safety must have constant maintenance by well-trained, intelligent, and motivated—read expensive—technicians.

Ducted Lift

The basic design of pointing a fan at the ground can be enhanced by putting it in a shroud or duct. The simplest example of this is the Hiller Flying Platform, a sort of flying Segway which flew over 50 years ago:



The duct, which forms an aerodynamic structure known as a Kort nozzle, amplifies the lift of the propeller by some 40%. (It also cuts down the noise.) The Flying Platform, like Verne's Albatross, used counter-rotating props. It was about 7 feet wide, weighed about 370 pounds empty, and could lift another 180 with a total thrust of 555 lbs. It used a total of 80 horsepower, one 40-HP engine for each propeller.

The version pictured was a 5-foot prototype, which could not get out of ground effect. The 7-foot version, and an 8-foot version designated VZ-1 by the Army, could, but even so had very limited altitude (33 feet) and speed (16 mph).[\[17\]](#)

It turns out that the duct around the propellers is both a blessing and a curse. It amplifies the lift of the props significantly. It also provides stability. The flying platform, especially the prototype 5-foot version, was easier to balance than a bicycle. Helicopters are inherently unstable; flying one is like balancing on a beach ball. With the duct around the fan, the flying platform is stable; any tilt or sideslip induces forces that tend to put it straight again. But that very stability limits its forward speed in the air.



The Army went on to test several more related vehicles, notably the VZ-6 and VZ-8 “flying jeeps,” which were essentially two VZ-1’s bolted together with the pilot sitting in between. Perhaps it is worth noting that the Army, for whatever reason, decided to farm out the VZ-6 to Chrysler, which had never built any flying machine, and the VZ-8 to Piasecki, a rival helicopter company to Hiller. The VZ-6 was a complete flop (literally—it flipped over in the air, crashed, and was cancelled), but the Curtiss-Wright VZ-7, a non-ducted fan quadrotor similar in configuration to today’s toy drones, more or less worked. The VZ-8 was reasonably successful, as a test vehicle. The Army Transportation Museum, where it resides in retirement, writes of it:

The Airgeep II used twin 400-hp Turbomeca Artouste IIC turbo-shaft engines that were linked, so if one failed the other would drive both rotors. One engine was linked to the landing wheels to move the machine around on the ground. The second model also had ejection seats for both pilot and co-pilot/gunner, and there was additional seating for three passengers.

Neither version of the VZ-8P was dependent upon the surface underneath for flight. Despite the fact that the Airgeeps were intended to operate within a few feet of the ground, both were capable of flying at altitudes of several thousand feet. They were stable and able to hover or fly beneath trees or between buildings. In addition, the Airgeep was surprisingly effective as a weapons platform.

Despite its many positive qualities, the Airgeep, like other ground effects machines developed during this period, was ultimately judged by the Army to be mechanically ill-suited to the rigors of field operations. The “flying jeep” concept was eventually abandoned in favor of further development of conventional battlefield helicopters.

Note in particular the step up that made the Airgeep into a useful vehicle: it had 800 horsepower’s worth of engine, compared to the Flying Platform’s 80.

As flying cars, flying jeeps had one of the main desiderata: versatility. They could take off and land anywhere. But they couldn’t compete with helicopters for speed, carrying capacity, and range, so the program was abandoned.

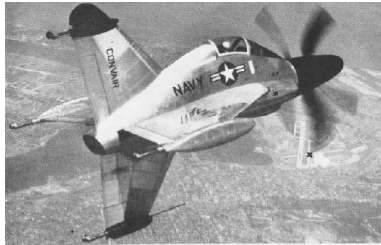
Tilt-wings

The US Army experimented with a number of VTOL designs of this description during the late 50s and early 60s: there were 9 VZ-series craft, of which the flying platform was just the first. The most successful of the basic designs used the obvious way to overcome the inefficiency of propellers, especially those with ducts, flying sideways through the air: tilt them as the machine transitions into forward flight.



The VZ-2 was representative of the type. It had two large propellers / small rotors (approximately 10 feet in diameter) mounted on a tiltable 25-foot wing. It had a 700-hp turbine engine and attained 128 knots in forward flight. It could transition from hover to cruise, or back again, in under a minute. [\[18\]](#) The VZ-2 was essentially a complete success as a research experimental vehicle, and was the forerunner of the V-22 Osprey in service today.

An even simpler way to tilt the wings than having them hinged to the fuselage is of course to tilt the entire airplane.



The Convair XFY Pogo and the Lockheed XFV Salmon (informally so called, after its test pilot), vintage 1954, were intended as fighter planes able to takeoff and land on helipad-sized decks on non-aircraft-carrier ships. They were both technically successful, but required a lot more skill to fly (particularly to land blind) and were not going to be able to compete in speed with jet fighters.

Ducted-fan powered-lift

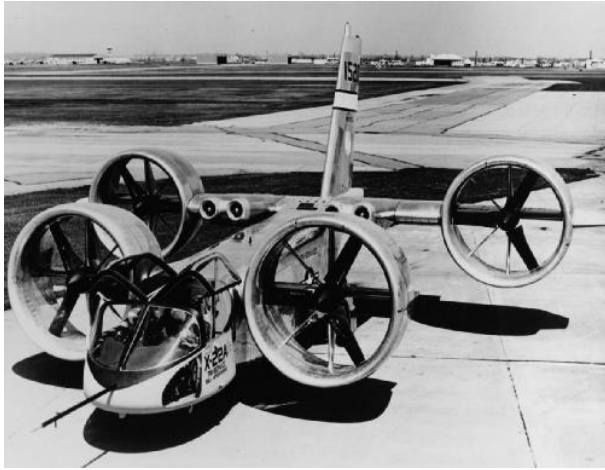
The Doak VZ-4 was based on the same basic idea as the VZ-2, but this time the props were ducted fans.



The surviving Doak VZ-4 is at the US Army Transportation Museum

The VZ-4 worked quite well. It turns out that having the wings fixed and the fans tilting is a better design than tilting the whole wing—note that today's V22 Osprey has this design feature. As an experimental aircraft, of course, things were learned from the VZ-4's performance and if it had gone into production, it could have been optimized quite a bit. Even so, it would

have made a perfectly usable flying car. It weighed about a ton empty and a ton and a half loaded. It had a maximum speed of 230 mph. About a decade later than the Army VZ program, in the mid-60s the Navy experimented with a 4-fan tilt-duct, the Bell X22-A:



Bell X-22A

The X22-A was essentially a flying bus, being nearly 40 feet long and 9 tons loaded. It proved once again that the tilting-duct concept was workable, being much easier to transition to forward flight than most of the other (remarkably numerous) experimental VTOLs of the 50s and 60s. The X22-A could takeoff and land vertically, and had a top speed of 255 mph. A scaled-down version might make just the kind of flying car we're looking for.

——Bottom Line——

In the 1930s, it was understood what would be needed in an aircraft “designed for the needs of the private owner.” The Autogiro might well have been just the thing to revolutionize private aviation. For one brief historical moment, we had the rare combination of the aeronautical genius in La Cierva, and a leading businessman with substantial engineering experience and resources in Pitcairn, both dedicated to bringing the flying car to the people. This hope was destroyed by the Great Depression and the war; average Americans could not afford cars, much less airplanes, until the later 40s.

In the Postwar World, the helicopter was the wonder of the age the way the autogyro had been in the 30s. Pitcairn had designed one helicopter during the war, the XR-9, which by all accounts was substantially more stable and easier to fly than the early offerings from *e.g.* Sikorsky, as Pitcairn’s engineering team had accumulated rotary-wing experience going back two decades. But Pitcairn stubbornly stayed with autogyros specifically because they were substantially less expensive and appropriately suited to the needs of the private owner. Then he spent the remainder of his life and fortune in court, with the government fighting tooth and nail all the way, instead of developing flying cars.

There is an amusing side note to the helicopter story. The pilot’s seat in an airplane is the left one, like the driver’s seat in a car. But the pilot’s seat in a helicopter (or gyroplane) is typically on the right. It turns out that while Pitcairn’s XR-9, and modern helicopters, are more stable and require only a light touch on the stick, the first widely used helicopter, the Sikorsky R-4, required a constant and somewhat tiring death-grip. So the pilots in the R-4 preferred to sit in the right seat to use their right hands on the (one per seat) stick, leaving the left to operate the (shared) between-seats collective control, the radio, and so forth. So a tradition started which has held to this day. [\[19\]](#)

By the 1970s, the mechanical and aerodynamic technology for flying cars of a variety of types—ranging from convertible airplanes to ducted-fan VTOLs—had reached the stage of successful experiments. These were

mostly military, and were at the time much too expensive for extensive private use. On the other hand, so were computers. There was no purely technological barrier to the continued development of flying machines, and another 50 years of improvement might well have given us VTOL flying cars. In the meantime, airplanes which would convert to a car and be driven to a destination from the nearest airport have not only been feasible but demonstrated since the 1930s, as have autogyros that could take off and land on a runway you could easily put on a one-acre lot. If mass-produced, such vehicles could be within the means of a substantial fraction of families today.

The bottom line is simple: We have to look elsewhere than technological feasibility for the reason we don't have flying cars.

3 The Graveyard of Dreams

I awoke to find the America I knew a total wreck—to find Americans a hunted race in their own land, hiding in the dense forests that covered the shattered and leveled ruins of their once magnificent cities, desperately preserving, and struggling to develop in their secret retreats, the remnants of their culture and science—and the undying flame of their sturdy independence.

—Philip Francis Nowlan, *Armageddon: 2419 A.D.*

*The fountains are dusty in the graveyard of dreams;
The hinges are rusty: they swing with tiny screams.*

—H. Beam Piper, *The Cosmic Computer*

In 1960, Detroit, Michigan was the epitome of American greatness. The automobile was the cornerstone of our economy, some would say culture. The Motor City had the highest per-capita income in the world. Economics professor Jay Zawatsky:

In 1960, before the Great Society, Detroit was the wealthiest city per capita in America among cities with more than two hundred thousand residents. In those years, the United States was the world's largest creditor nation. Today, Detroit is the poorest city per capita in America among cities with more than two hundred thousand residents. Today, the United States is the world's largest debtor nation.

Canadian pundit Mark Steyn puts it with a little more tongue in cheek:

By the time Detroit declared bankruptcy, Americans were so inured to the throbbing dirge of Motown's Greatest Hits—40 percent of its streetlamps don't work; 210 of its 317 public parks have been permanently closed; it takes an hour for police to respond to a 9-1-1 call; only a third of its ambulances are driveable; one-third of the city has been abandoned; the local realtor offers houses on sale for a buck

and still finds no takers; etc., etc.—Americans were so inured that the formal confirmation of a great city’s downfall was greeted with little more than a fatalistic shrug. But it shouldn’t be. To achieve this level of devastation, you usually have to be invaded by a foreign power.

There are 70,000 abandoned buildings; a third of the city’s area is vacant or derelict. The murder rate is 11 times that of New York; less than 10% of crimes are solved by police. The population has fallen by 60 percent since the days of greatness, and Detroit’s per capita income is now the lowest in the country. [\[20\]](#) Houses are being demolished (with federal funding) at the rate of 200 a week. [\[21\]](#)

Talk about dusty fountains in the graveyard of dreams. A recent CNN/ORC poll found that 75% of Americans are dissatisfied with how things are going these days. In 1962, Pew Research tells us, about 75% of Americans trusted the government. In 2016, less than 20% did. It is clear that the prevailing zeitgeist of expectations for the future today is far more pessimistic than it was in 1962, and this has nothing to do with the failure of one or two individual technological projections. This is captured in the mood and tone of the movies evoked by this quip from Paul Graham:

It’s hard to predict what life will be like in a hundred years. There are only a few things we can say with certainty. We know that everyone will drive flying cars, that zoning laws will be relaxed to allow buildings hundreds of stories tall, that it will be dark most of the time, and that women will all be trained in the martial arts.

He’s referring to the now-standard *film noir* depiction of the future city as seen in films such as *Blade Runner*: a world dark, hard, and artificial, where life is nasty, brutish, and short—in a word, uncivilized.

Charlie Stross, the British science fiction writer, writes in his “21st Century FAQ” [\[22\]](#)

Q: What can we expect?

A: Pretty much what you read about in *New Scientist* every week. Climate change, dust bowls caused by over-cultivation necessitated by

over-population, resource depletion ...

And it's not just Stross; it's the *New Scientist* itself, the kind of popular science/technology magazine that 50 years ago would have been the leading edge of technological optimism, all full of flying cars and hope.

I Have Seen the Future

It is very easy and cheap to travel by air. The airplanes are very small and very fast. They seat thirty people and fly them through the sky at over 4,000 miles per hour.

Seats are not reserved in advance. You just climb aboard. It is just like the town bus service.

—Geoffrey Hoyle, 2011: *living in the future* (1972)

Heeding the warning of these forecasting missteps, let us assume that innovation continues, with such marvels as the driverless Google car on the near term horizon. Research on the genome will surely make progress in the fight against cancer and other diseases. But research for new blockbuster drugs is encountering diminishing returns, with a substantial numbers of failures and rapidly escalating costs of experimentation per successful new drug found. And, just as we should heed the lesson of the four overly pessimistic quotations from the Western Union to Bill Gates, so we should also recall the past overoptimism, including the universal prediction in the late 1940s that within a generation each family would have its own vertical lift-off airplane, a universal society of Jetsons.

—Robert J. Gordon

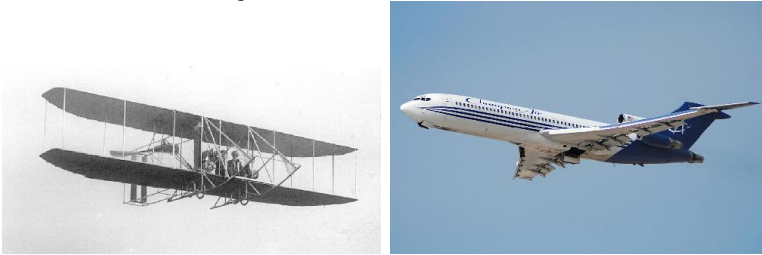
We're very far from the flying car.

—Tyler Cowen

To the people of 50 years ago, including my 8-year-old self in 1962, it was inconceivable that we would be using the same flying machines now as we did then. “What will our transportation technology look like in 50 years?” you might have asked them.

And they would have answered: “Well, look what it was like 50 years ago in 1912!” The vast majority of people had never even seen a flying

machine. The brothers Wright had only just begun selling the Wright Model B, the first production airplane. Louis Blériot had just crossed the English Channel (Calais to Dover, about 25 miles at 40 knots) in a machine that looked like a kite tied to a tricycle with baling wire—and caused a worldwide sensation. The Fokkers and Sopwith Camels of the WWI flying aces were still years in the future.



50 years.

But by 1962, fighter planes such as Lockheed's F-104 Starfighter flew at over 1300 mph. A bomber such as the B-52, which had been in production for 10 years, had a loaded weight of over 250,000 pounds and a range of over 10,000 miles. Even the commercial airliners of the day, such as the 727 and the DC8, could carry 170 people 5000 miles at 600 mph.

Over the same period, the automobile, which had been a toy for only the rich in 1912, had become universally owned. Indeed, it had become so ubiquitous that it was a cornerstone of the American way of life. If the Rolls Royces, Packards, and Duesenbergs of the Teens could pave the way to Fords and Chevys for everyone 50 years later, surely the Beechcraft, Mooneys, and Sikorskys of the Sixties could lead to Pipers, Cessnas, and Hillers for all today.

Or rather, to something as far beyond the Pipers, Cessnas, and Hillers of the Sixties as they themselves were beyond the Wright Model B or the Blériot XI. But what happened is that the general aviation industry, which had been healthy and growing nicely into the Seventies, crashed in the Eighties, with most private plane manufacturers going broke or abandoning that part of their business.

People in 1962 had a very reasonable basis for expecting technological progress to improve their lives a lot in the coming decades. It had done so substantially in the previous decades. The life of the average American in

1962 was enormously better than it had been in 1900. Obvious changes were the automobile itself, flying machines, skyscrapers, antibiotics, movies, pre-made clothing, electric lighting and power in the home, radio, television, refrigerators, vacuum cleaners, washing machines, and stoves that turned on with a touch of a button instead of your having to build a wood fire in them.

You plowed your field with a tractor instead of a mule, but more likely you bought your groceries at a store. You sewed your clothes with a sewing machine, but more likely you bought them pre-made. Not only did you have a car, but there was a rapidly-growing interstate highway system upon which you could drive at speed and in comfort.

Furthermore, people could afford to buy the new machines and products. The average American had become 3 to 4 times richer from 1900 to 1962. GDP per capita grew from \$4000-5000 (constant 2005 dollars) in 1900 to \$16,000 in 1962. Personal income as a fraction of total productivity remained consistent at roughly 50% throughout the period. Behind the scenes, a host of innovations from assembly-line manufacturing to containerized cargo shipping boosted productivity and brought luxuries previously reserved for the most wealthy within the reach of most everyone. Surely it was reasonable to imagine that the same kind of progress that had made the automobile, a plaything for the very rich in 1910, into an indispensable adjunct of the average family by mid-twentieth century, could do the same with the private aircraft by the mid-twenty-first.

Surely it was reasonable to imagine that flying machines themselves, which the scientific community firmly believed impossible in 1900, but which had reached supersonic speed in 1947 while Orville Wright was still alive, and were carrying passengers in intercontinental jets in 1962, might carry humans to the planets by 2062.

Surely it was reasonable to imagine that after advances in medicine that added three decades to average lifespan, further advances, possibly even rejuvenation, were in prospect?

Surely it was reasonable to imagine that the tall buildings of the 21st century might tower over those of the 20th, as they themselves did those of the 19th?

Surely it was reasonable to imagine that mechanization and automation, which had reduced the effort necessary to farm, manufacture, and keep

house by an order of magnitude in the 20th century to date, would continue and remove almost all necessary effort?

The Jetsons was a prediction almost entirely of technological improvement. Social, political, economic, and legal arrangements were firmly and recognizably rooted in the 1960s. In this sense it was considerably more conservative than H. G. Wells' writings, which while exalting technological progress, also firmly embraced world government, public ownership of capital, and centralized planning on a grand scale, and imagined a cultural revolution in the direction of free love. Various other Twentieth Century science fiction experimented with similar ideas, generally imagining that technology could improve the other areas: we have Isaac Asimov's computer-controlled economy and wise robotic overlords; E. E. Smith's galactic government of wise, incorruptible Lensmen; Asimov again with a science, psychohistory, that could predict economic and political trajectories a thousand years into the future and could be used to optimize them; Heinlein with an anarchocapitalistic, polyamorous society set on the Moon declaring its independence from Earth. But whatever futures it envisioned, mid-century science fiction—the future we were promised—reflected the generally optimistic, can-do attitude of American society of the period. That seems to be missing today, replaced with a defeatist spiritual malaise. Was the Sixties' technological optimism warranted? Are we better off now than then? Will we be better off still in another 50 years?

Stagnation Point

I wanted the hurtling moons of Barsoom. I wanted Storisende and Poictesme, and Holmes shaking me awake to tell me, “The game’s afoot!” I wanted to float down the Mississippi on a raft and elude a mob in company with the Duke of Bilgewater and the Lost Dauphin.

I wanted Prester John, and Excalibur held by a moon-white arm out of a silent lake. I wanted to sail with Ulysses and with Tros of Samothrace and eat the lotus in a land that seemed always afternoon. I wanted the feeling of romance and the sense of wonder I had known as a kid. I wanted the world to be what they had promised me it was going to be—instead of the tawdry, lousy, fouled-up mess it is.

— Robert A. Heinlein, *Glory Road*

We wanted flying cars, instead we got 140 characters.

—Peter Thiel



You call this the future?

(CALVIN AND HOBBS © 1989 Watterson. Reprinted with permission of UNIVERSAL UCLICK. All rights reserved.)

“You call this the future?” Calvin (the little boy) famously complains to Hobbes (the imaginary tiger) in the cartoon. “Where are the flying cars?” That was December 30, 1989. A quarter century has gone by, and we’re still waiting. The question “Where is my flying car?” Wikipedia tells us, “is

emblematic of the supposed failure of modern technology to match futuristic visions that were promoted in earlier decades.” A Google search for the question returns 781,000 webpages. Flying cars have become a symbol of a mismatch: the future as imagined in the first half of the 20th century seemed a lot brighter than the present we’re living in now. We have seen the future, and it doesn’t work as well as we expected. Progress has slowed to a crawl. Or is that merely perception?

After all, in 1989 there was no Wikipedia and no Google. Indeed there were no webpages. The World Wide Web would make its public appearance, at the CERN laboratory in Europe, in 1991. The Internet itself connected mostly researchers at universities and government labs. As cyberpunk author William Gibson observed, “The future is already here—it’s just not very evenly distributed.”

Adam Gurri, blogging at *the Umlaut*, wrote

We wanted flying cars, instead we got the ability to instantly connect with anyone anywhere in the world, to share stories, pictures, music, podcasts, ideas, film, animation, comics, feedback, friendship, love, and our lives. Flying cars seem really cool on their face, but I somehow doubt that they would have so meaningful an impact on our lives.

George Jetson didn’t even have a cellphone.

So, did the predictors of a half-century ago merely miss the mark? Kevin Drum, blogger at *Mother Jones*, thinks so:

The argument here is that back in the 1950s we thought the future would bring us flying cars, electricity too cheap to meter, and vacations on the moon. But none of that has happened. What gives?

The answer is prosaic: Forecasters in the ’50s were wrong. It’s not that the future never arrived—it’s that the future brought us different stuff than we thought we were going to get. Our lack of flying cars simply doesn’t tell us anything about the pace of innovation. [\[23\]](#)

Clearly there's more progress in some areas than expected, to match the less progress that happened in such things as flying cars. To some extent, even this was predicted: Arthur C. Clarke, in *Profiles of the Future*, offers one of the best explanations from a purely technical point of view, about why progress in fast transport might have fallen short of predictions. He is not, he reminds us, in the business of offering specific predictions, especially with dates attached, but of sketching out the general envelopes of capability each form of technology might be expected to fill in in the arbitrary future. But, as he points out, technologies substitute:

There is, however, one trend which may work against the establishment of a virtually instantaneously global transportation system. As communications improve, until all the senses—and not merely vision and hearing—can be projected anywhere on the face of the Earth, men will have less and less incentive to travel. This situation was envisioned half a century ago by E. M. Forster in his famous short story “The Machine Stops,” where he pictured our remote descendants as living in single cells, scarcely ever leaving them but being able to establish instant TV contact with anyone else on Earth, wherever he might be.

In his own lifetime Forster has seen TV perfected far beyond his imaginings of three decades ago, [\[24\]](#) and his vision of the future may be, in its essentials, not so far from the truth. Telecommunication and transportation are opposing forces, which so far have always struck a balance. If the first should ever win, the world of Forster's story would be the result.

Is there some discernable pattern to the flying car mispredictions? Is the promised future simply late? If so, when will it get here? Or was it ever realistic to begin with?

Drum was, after all, writing in reaction to a number of recent commentators claiming that meaningful innovation has slowed to a crawl in the latter 20th century. Many people (including myself in *Nanofuture*), have pointed out that the second half of the 20th century didn't seem to bring nearly as many major, serious advances as the first half. No less than Ben Bernanke,

Chairman of the Federal Reserve, said essentially the same in a commencement address:

The comparison of the world of 1963 with that of today suggests quite substantial but perhaps not transformative economic change since then. But now let's run this thought experiment back another 50 years, to 1913 (the year the Federal Reserve was created by the Congress, by the way), and compare how my grandparents and your great-grandparents lived with how my family lived in 1963. Life in 1913 was simply much harder for most Americans than it would be later in the century. Many people worked long hours at dangerous, dirty, and exhausting jobs—up to 60 hours per week in manufacturing, for example, and even more in agriculture. Housework involved a great deal of drudgery; refrigerators, freezers, vacuum cleaners, electric stoves, and washing machines were not in general use, which should not be terribly surprising since most urban households, and virtually all rural households, were not yet wired for electricity. In the entertainment sphere, Americans did not yet have access to commercial radio broadcasts and movies would be silent for another decade and a half. Some people had telephones, but no long-distance service was available. In transportation, in 1913 Henry Ford was just beginning the mass production of the Model T automobile, railroads were powered by steam, and regular commercial air travel was quite a few years away. Importantly, life expectancy at birth in 1913 was only 53 years, reflecting not only the state of medical science at the time—infection-fighting antibiotics and vaccines for many deadly diseases would not be developed for several more decades—but also deficiencies in sanitation and nutrition. This was quite a different world than the one in which I grew up in 1963 or in which we live today.

It is my perception that what they say about the effects of technology on the average person is quite true. The *Leave It to Beaver* family of the 50s had a life that was essentially as comfortable as ours is today, but worlds removed from that of the turn of the 20th century. Improvements since then, as seen

by the average person, have consisted in remarkably large part of decoration or entertainment.

Brennschluss

It is nearly 50 years since I sat glued to a grainy black-and-white TV set and watched Neil Armstrong and Buzz Aldrin land on, and then step out on, the Moon. If you had asked me then, I would have blithely assured you that by the year 2000, much less 2019, I'd have my own spaceship, or at least own a flying car and be able to buy tickets on a spaceship to the big celebration at Tranquility Base.

It didn't work out that way. Indeed, not only am I not going to be celebrating on the Moon, nobody is going there for any purpose whatsoever. Only 12 men have ever walked on the Moon. All of them were born while Orville Wright was still alive and no one had flown a jet. Only Aldrin, Duke, Schmitt, and Scott are still alive as of this writing; Armstrong, Bean, Cernan, Conrad, Irwin, Mitchell, Shepard, and Young are gone. John Glenn, last of the original 7 Project Mercury astronauts, died in 2016 at the age of 95. Godspeed...

*I am, and ever will be, a white socks, pocket protector, nerdy engineer.
And I take a substantial amount of pride in the accomplishments of my
profession.*

—Neil Armstrong

Flatline

The object of this Part is to bridge, as rapidly and vigorously as possible, the transition from the year 1970 to the year 2054. An age of enormous mechanical and industrial energy has to be suggested by a few moments of picture and music.

—H.G. Wells, *Things to Come* script

[Hiatus] *Little research and only minor technical advances during this period. Extreme puritanism. Certain aspects of psychodynamics and psychometrics, mass psychology and social control developed by the priest class.*

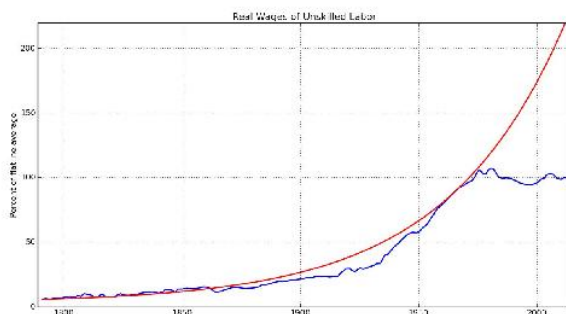
—Robert A. Heinlein, *Future History Timeline*

*People don't want to think that technology is broken ...
Pharmaceuticals, robotics, artificial intelligence, nanotechnology —all these areas where the progress has been a lot more limited than people think. And the question is why.*

—Peter Thiel

A lot of the recent commentary about the slowing or not of technological progress was engendered by the 2011 appearance of *The Great Stagnation* by GMU economist Tyler Cowen. (*TGS* itself may have been prompted in part by some observations of techno-entrepreneur Peter Thiel.) The thesis of the book is that there has been a slowdown in the US economy apparent since the '70s. This is reflected in a slowdown in the growth of income and the loss of the American Dream that your children will have a better life than you did.

Cowen uses median income rates to argue for the Great Stagnation, but we can also see it in this flatline in wages of unskilled labor, from statistical historian Peter Turchin:



Data from Turchin, Ages of Discord, figure 3.3. The smooth line represents a steady 2% growth rate for comparison.

This is perhaps the most striking example, but Turchin points out that the entire set of trends he tracks shifted from a favorable (“integrative phase”) to an unfavorable (“disintegrative phase”) direction in the 1970s.

What’s worse is a phenomenon that some economists (including Cowen) have taken to calling “cost disease,” which is infecting more and more of modern life, but which really began showing up in a big way during the Great Stagnation. We are used to prices going up because of inflation, but there are some things—typically the most important things—whose costs keep stubbornly going up in real terms, i.e. *even adjusted for inflation*. Housing costs twice as much, on average. Primary education costs three times as much as in the 60s, and children are not learning more. Until the Seventies, health care costs and longevity in the US grew at about the same rates as in comparable developed countries; since then longevity has grown more slowly and costs have grown much faster. Medical care now costs six times as much as in the 60s: in 1960, the average worker worked ten days to pay for his health insurance; today, 60 days. [\[25\]](#) College tuition and textbooks cost in the neighborhood of ten times as much. Subways used to cost \$5 million a mile; now, in New York anyway, \$3 *billion* a mile.



The difference between GDP per capita (net of government spending) and the postwar trend of steady 2.5% growth.

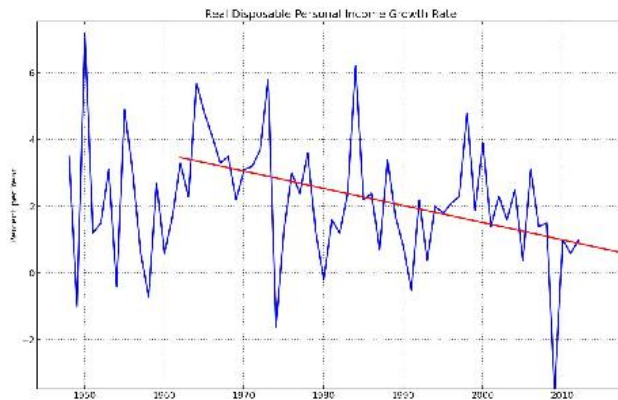
In the Seventies, actual economic growth fell below a constant-growth trend line and never regained it. We went into a secular decline that has us further from the curve now (in dollar terms) than we were in the depths of the Great Depression itself. In the four decades prior to 1970, the per capita gdp had a growth rate of 2.8%; in the four decades after, 1.9%. You can see that in the postwar era (*i.e.* 1945-1975), we stayed quite close to a constant

growth-rate curve. If you were a futurist in the Sixties, you can be forgiven for assuming that we had the economic know-how capable of sustaining that growth—we had demonstrated it for a quarter-century. In fact, futurists in the Sixties believed exactly that:

The most significant discovery emerging from our increasingly sophisticated understanding of the economic growth process is the fact that accelerated economic growth can be achieved by a combination of fiscal policy, monetary policy, and continuously increasing R&D budgets (both Federal and private).

That was Robert Prehoda writing in *Designing the Future* (emphasis, the entire quoted passage, in the original), in 1967. [\[26\]](#) A 1966 book entitled *The Shape of Automation*, by Herbert Simon, one of the founding fathers of Artificial Intelligence who would go on to win the Nobel Prize in Economics, said essentially the same: that because of the increasing productivity due to automation the average family income would reach \$28,000 (in 1966 dollars) after the turn of the century. An easy rule of thumb for translating 1960s dollars to current-day ones is to multiply by 10. Note Simon's projection was only for a 3% growth rate. This was not a ridiculous assumption; real family income had grown at roughly 2.5% in the previous 50 years. If "*our increasingly sophisticated understanding of the economic growth process*" had been real, it should have been pretty easy to bump it up another half percent. But what actually happened in the succeeding half-century is that family income only grew at 0.5%. [\[27\]](#) It's not unreasonable to suppose that something went wrong, although it isn't clear exactly what. For example, over the period the number of single-parent households rose much faster than the population as a whole; lower family income doesn't necessarily mean lower per capita income. But it does mean that many of the economic efficiencies that a traditional family structure provided have been lost.

Furthermore, we can see the same effect in personal disposable income growth rates: a linear regression since 1962 shows a consistent decline. [\[28\]](#) Growth of disposable income is nearly over; after the 2020s it will be shrinking.

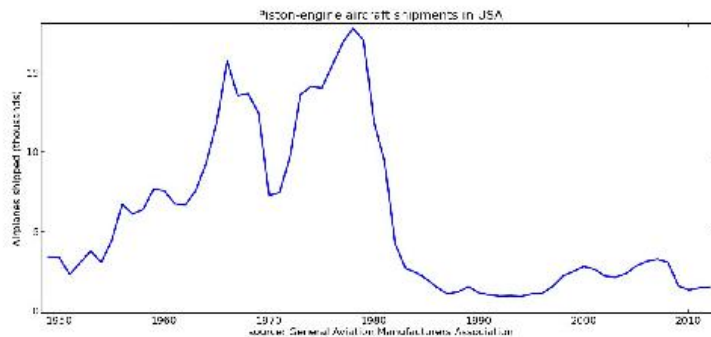


No wonder we're getting more pessimistic. (The regression line, by the way, is somewhat over-optimistic given the "Great Recession" of 2008-date.) Any one of these indicators of a stagnation might readily be explained away as reflecting a different trend, or as a misunderstanding of the statistics by your admittedly non-economist author. But it is difficult, I think, to dismiss all of them.

... our main problem is that all the most important things cost ten times as much as they used to for no reason, plus they seem to be going down in quality, and nobody knows why, and we're mostly just flailing around looking for solutions ...

—Scott Alexander

The Airplane Crash



The private airplane industry crashed around 1980.

Another thing that happened right around the end of the Seventies was that the private airplane industry, including companies such as Cessna and Piper, which had both been founded in 1927, mysteriously disappeared.

The 1960s had been a boom time for private aviation; Jules Bergman's 1964 *Anyone Can Fly* has a 40-page appendix displaying the various makes of small family-sized airplane available to private owners.

In the graph above of private (piston-engined propeller) airplanes shipped, you can see the energy crisis as the dip around 1970, but the industry had bounced back from that in half a decade. It was perfectly reasonable to have expected, in the 60s and 70s, a continued increase in the numbers, quality, performance, and capabilities of private airplanes. But it didn't happen.

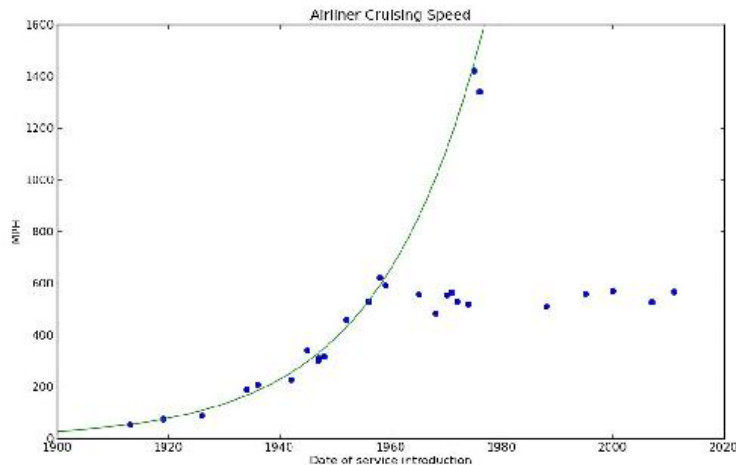
Due to WWII era federal pilot-training and training-aid programs, licensed pilots in the US increased from 50,000 in 1940 to 350,000 in 1950. In 1946, a record 35,000 general aviation planes were sold. Industry estimates were that there was a market for 100,000. That boom and bust was almost certainly a misreading of the market. The 1980 collapse was not. Today only about 700 new piston airplanes are sold each year, and about 400 turboprops and 400 private jets.

As you might guess, airplanes cost more than ten times what they did in the 70s. Airplanes are just one more example, although a particularly telling and extreme one, of the general "cost disease" trend.

Speed Trap

There were other, less obvious falterings as well. For a graphic demonstration, you can't do much better than looking at airliner speeds.

[29] They rose on a nice exponential growth curve until the Sixties, and then flatlined:



Airliner speed vs date. The curve is a simple exponential fit to points before 1960.

This particular plateau can be explained easily enough by physics and economics: it's 3 times as expensive to fly just above Mach 1 as just below it. The Concorde SST was heavily subsidized as a national prestige project by Great Britain and France (as was the similar Tupolev-144 by the USSR—see the two dots at the top of the chart). As a measure of what the technology was capable of, though, those two aircraft fell right on the trend line, as you can see. For example, the de Havilland Ghost turbojet engine in the 50s had 5000 pounds of thrust; the GE90 of the 90s has 115,000. The people of 1962 had seen a solid order of magnitude increase in the speed, *and* in the range, *and* in the carrying capacity of available aircraft in the previous 50 years. Geoffrey Hoyle's 4000 MPH airliner was in fact a fairly conservative prediction for 2011. Without the flatline, that is; the trend curve was at roughly 10,000 MPH then.

Don't forget the other figures of merit, either. Airliners should have been getting more capacious and comfortable at the same time as they were getting faster, as they had been since the days of the Ford Tri-Motor. In the 50 years since the flatline, we've seen virtually nothing; indeed, the average airliner today is somewhat slower (and more cramped) in a bid for fuel efficiency. And yet in those 50 years, it seems almost certain that, especially given the rise of a substantial trans-Pacific trade, there is a market for cutting say 6 hours off the LA-to-Tokyo travel time. The

technology to do so certainly exists. So while there is a “rut” in design and economy space for airliners, the fact that we have been stuck in it for half a century remains a good indication that there is some other roadblock in the way of technological improvement. In fact, it turns out that for long international flights (e.g. LA-Sydney), the energy used by a jetliner dragging its way through the atmosphere is just as much as would have been needed to put it into orbit—and make the trip in less than an hour. So we can reasonably use the plateau in air travel as an iconic, if perhaps exaggerated, example of the general plateauing of life-improving technology that happened in the 70s and 80s.

Running on Empty

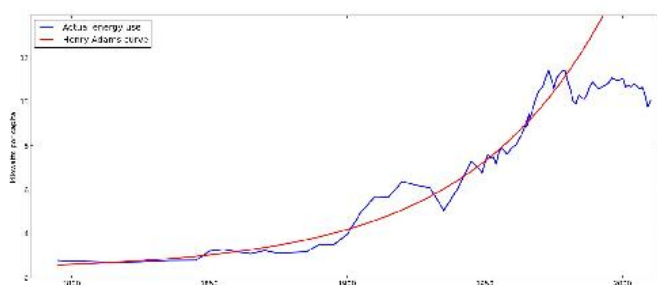
We could have predicted over the last few years what the American government’s policies on oil and natural gas would be if we had assumed that the aim of the American government was to increase the power and income of the OPEC countries and to reduce the standard of living in the United States.

—(Economics Nobel laureate) Ronald Coase (1981)

Henry Adams, scion of the house of the two eponymous Presidents, wrote in his autobiography about a century ago:

The coal-output of the world, speaking roughly, doubled every ten years between 1840 and 1900, in the form of utilized power, for the ton of coal yielded three or four times as much power in 1900 as in 1840. Rapid as this rate of acceleration in volume seems, it may be tested in a thousand ways without greatly reducing it. Perhaps the ocean steamer is nearest unity and easiest to measure, for any one might hire, in 1905, for a small sum of money, the use of 30,000 steam-horse-power to cross the ocean, and by halving this figure every ten years, he got back to 234 horse-power for 1835, which was accuracy enough for his purposes.

In other words, we have had a very long-term trend in history going back at least to the Newcomen and Savery engines of 300 years ago, a steady trend of about 7% per year growth in usable energy available to our civilization. Let us call it the “Henry Adams Curve.” The optimism and constant improvement of life in the 19th and first half of the 20th centuries can quite readily be seen as predicated on it. To a first approximation, it can be factored into a 3% population growth rate, a 2% energy efficiency growth rate, and a 2% growth in actual energy consumed per capita. Here is the Henry Adams Curve, the centuries-long historical trend, as the smooth red line. Since the scale is power per capita, this is only the 2% component. The blue curve is actual energy use in the US, [30] which up to the 70s matched the trend quite well. But then energy consumption flatlined.



Energy consumption per capita in the US. One kilowatt, of course, equals 8,766 kilowatt-hours per year.

The 1970s were famously the time of the OPEC oil embargo and the “energy crisis.” But major shortages preceded the embargo by a year or two. They were caused by Nixon’s energy price controls, instituted in 1971. The embargo wasn’t until 1973.

If you didn’t know better, you would think that the Department of Energy was established (August 4, 1977) intentionally to prevent energy use. Before the Industrial Revolution, most of the power humans used was their own muscles, or those of domestic animals. A human eating a 2000-calorie per day diet averages about 100 watts. The average South American today uses 10 times that amount of power, and the average North American 100 times. It doesn’t seem unreasonable at all to imagine another industrial revolution giving us another factor of ten, or even another 100. We would

already be up an extra factor of 2 or 3 by now if we had only continued the energy trajectory we were on before 1970. And we might just have had flying cars, space travel, and the rest before 2062.

——Bottom Line——

“Is there any other point to which you would wish to draw my attention?”

“To the curious incident of the dog in the night-time.”

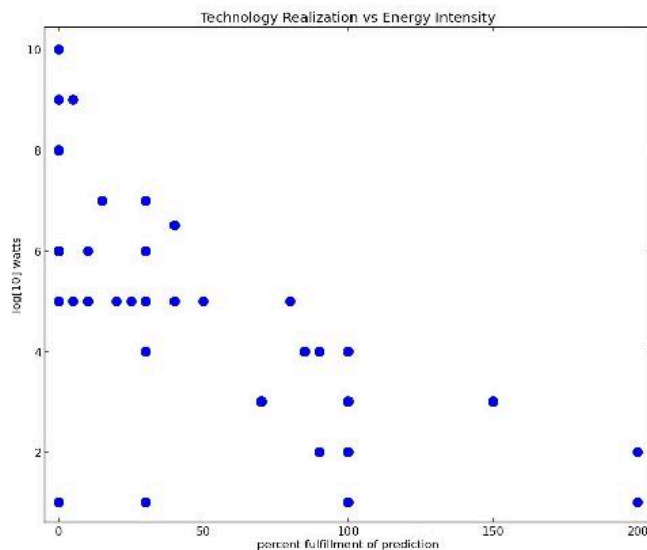
“The dog did nothing in the night-time.”

“That was the curious incident,” remarked Sherlock Holmes.

—The Adventure of Silver Blaze

Hence the perception that there has been a marked drop-off in the technological advances that made a big difference in people’s lives. We’ve already seen the list of life-changing technologies that revolutionized the early twentieth century, up to and including the automobile itself, and the relative lack of same in the latter half.

We can chart the predictions of future technology by the Golden Age SF writers and futurists of the 50s and 60s by the degree to which they came true versus how much energy each technology might need to use:



Technologies predicted in science fiction ca. 1960, with percent of fulfillment today vs energy intensity. Details in Appendix E.

On the power scale, our current energy flatline of 10 kW is a 4; there are technologies at most degrees of attainment below 100% at that power level. Similarly, there are technologies that just fulfilled predictions at every power level below 10 kW.

But there is a clear boundary. The extent to which a technology didn't live up to its Jetson's-era expectations is strongly correlated with its energy intensity. The one area where progress continued most robustly—Moore's Law in computing and communications—was the one where energy was not a major concern. It was my privilege—blind luck, really—to have spent most of my working scientific life in that area, and so I arrived at the Twenty-first century with some sense of how it should have been—indeed, *how it had been* for everyone in the technological enterprise up until my benighted generation.

There has been considerable advance in aeronautical engineering since then, but it hasn't shown up in faster, roomier airliners or flying cars. Most of that considerable effort and ingenuity has gone to energy efficiency. We now have small, sleek private planes that use half the fuel per mile that my old Beechcraft does. What we don't have, but could have had instead with the same amount of work, would be flying machines that were somewhat less efficient for pure flying because they also were cars. They could also be a lot quieter on takeoff, but known noise reduction techniques, such as slower propellers with more blades, are less energy efficient than current practice. Planes are made lighter by the highest-tech carbon fiber composites, and therefore more fuel-efficient—but also much more expensive.

Arthur C. Clarke, in *Profiles*, spent an entire chapter on GEMs—hovercraft. Hovercraft are fairly rare today, mostly used as military landing craft and a few sporting and ferry applications. But Clarke had envisioned them replacing a substantial portion of seagoing cargo ships. It is perfectly feasible to build GEMs that big; their efficiency improves with size. Furthermore they would not only have been faster across the oceans, but they wouldn't need canals or docks—they could proceed across any reasonably level ground (or ice). This could have changed the face of worldwide shipping as much as containerization. But the GEM uses more power than a boat.

In 1973, the FAA banned civilian supersonic flight over the United States. The ostensible reason was noise, although the activists responsible for the push enormously exaggerated it. One of the major avenues of technological improvement we rightly expected in the 1960s was faster airliners. 40 years of advancement in aeronautics would let us field supersonic airliners that were much quieter today; but the ban remains, in a classic Catch-22 where there are no actual sonic boom noise standards, but the FAA wants to see the airplane first and then they'll decide on the rule. In this case, we got the double whammy of energy starvation and regulatory strangulation. The speeds trend curve says we should have airliners that do 10,000 mph (about half orbital speed) by now. With a gentle (1-G) acceleration (taking 5 minutes and 250 miles, and the reverse to slow down), that would take you from New York to San Francisco in 22 minutes.

Power is our only lack. We generate all we can with the materials and knowledge at our disposal, but we never have enough. Our development is hindered, our birth-rate must be held down to a minimum, many new cities which we need cannot be built and many new projects cannot be started, all for lack of power.

—E. E. “Doc” Smith, *Skylark Three*

4 Waldo and Magic, Inc.

Waldo

In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

—Richard P. Feynman (1959)

In 1942, Robert A. Heinlein, under the pseudonym of Anson MacDonald, published the cover story in the leading SF magazine, *Astounding*. This story introduced the “Waldo F. Jones Synchronous Reduplicating Pantograph.” Heinlein is recognized as the conceptual inventor of the telemanipulator, often termed a “waldo” for that reason. These came into use in the ’50s, with the push of the rapidly-developing science of cybernetics/control theory, and the pull of the necessity of working with radioactive materials in the rapidly-developing nuclear field. It is not as widely remembered that the original waldos in the story were (a) self-replicating (“Reduplicating”) and (b) scale-shifting (“Pantograph”). Waldo’s construction of a series of ever-smaller waldos is with the goal of being able to operate on individual nerve cells.

... Neither electromagnetic instruments nor neural surgery was refined enough to do accurate work on the levels he wished to investigate. But he had waldos. The smallest waldos he had used up to this time were approximately half an inch across their palms—with micro scanners to match, of course. They were much too gross for his purpose. ... He used the waldos to create tinier ones. ... His final team of waldos used for nerve and brain surgery varied in succeeding stages from mechanical hands nearly life size down to these fairy digits which could manipulate things much too small for the eye to see. They were mounted in bank to work in the same locus. Waldo controlled them all from the same primaries; he could switch from one size to another

without removing his gauntlets. The same change in circuits which brought another size of waldos under control automatically accomplished the change in sweep of scanning to increase or decrease the magnification so that Waldo always saw before him in his stereo receiver a “life-size” image of his other hands.

Note that Heinlein even addresses, in an offhand science-fiction kind of way, the problem of seeing what you are doing at smaller scales. But that’s all. It’s an idea, not a detailed plan of any kind. But it seems almost certain that the young Richard Feynman would have read *Waldo* or known about it. He had been after all an undergraduate at MIT, at the time perhaps one of the very biggest hotbeds of science fiction fandom. And note the reference to “atomic energy plants,” where the telemanipulators were in those days commonly referred to as waldos, in the talk discussed below.

Whatever his inspiration, Feynman, by then a professor of physics at Cal Tech who had already done the revolutionary work for which he would win the Nobel Prize, had been tapped to give the after-dinner speech at an American Physics Society conference in late 1959. So to have something fun but intriguing to catch the audience’s interest, he dusted off the Waldo idea and, being Feynman, went over it in detail and put a reasonably sound technological and scientific basis under it—and became impressed with the unsuspected implications and possibilities.

The Problem

In 1997, Philip Collins, then a graduate student at Berkeley, won the Foresight Institute’s Distinguished Student Award for his experimental verification that a defect location in a carbon nanotube could form a near-perfect rectifier, as well as various other heterojunction device behaviors (e.g. transistors), as had been theoretically predicted just the year before. “Such junctions could provide electronic elements with sizes inaccessible by lithographic manufacturing.” [\[31\]](#)

In the decade afterward, a wide variety of electronic devices and phenomena were found in carbon nanotubes, including highly conductive wires and FETs. Yet no nanocomputer or other complex circuit was built for

a decade and a half. [\[32\]](#) We had the devices. What we do not have, still, is simply the infrastructure that macroscopic technology takes for granted: the ability to sort and test parts; to cut and join materials; to create frameworks that can hold devices in designed relationships, and the ability to place parts into such frameworks.

And yet we should have. In 1959 Feynman, in his now-famous talk *There's Plenty of Room at the Bottom*, had described a straight-forward, immediately actionable plan which would have resulted in exactly such an infrastructure well before 2000 if it had been followed.

Feynman's Proposal

Let us begin by quoting the relevant section of Feynman's talk: [\[33\]](#)

Now comes the interesting question: How do we make such a tiny mechanism? I leave that to you. However, let me suggest one weird possibility. You know, in the atomic energy plants they have materials and machines that they can't handle directly because they have become radioactive. To unscrew nuts and put on bolts and so on, they have a set of master and slave hands, so that by operating a set of levers here, you control the "hands" there, and can turn them this way and that so you can handle things quite nicely.

... Now, I want to build much the same device—a master-slave system which operates electrically. But I want the slaves to be made especially carefully by modern large-scale machinists so that they are one-fourth the scale of the "hands" that you ordinarily maneuver. So you have a scheme by which you can do things at one-quarter scale anyway—the little servo motors with little hands play with little nuts and bolts; they drill little holes; they are four times smaller. Aha! So I manufacture a quarter-size lathe; I manufacture quarter-size tools; and I make, at the one-quarter scale, still another set of hands again relatively one-quarter size! This is one-sixteenth size, from my point of view. And after I finish doing this I wire directly from my large-scale system, through transformers perhaps, to the one-sixteenth-size servo motors. Thus I can now manipulate the one-sixteenth size hands.

Well, you get the principle from there on. It is rather a difficult program, but it is a possibility.

In a nutshell, the idea is to start from macroscale machining and fabrication and move to the nanoscale *without ever losing the ability to do general fabrication and manipulation*. That's exactly how Waldo did it in the Heinlein story. *It is a possibility*.

In working up the talk, it would appear, Feynman got a glimmering of just how powerful a technology lay in that direction. He famously offered prizes for the first steps along such a pathway, \$1000 each for a tiny motor and tiny writing, hoping to kickstart interest. It may help to understand how important he considered it to realize that \$1000 in 1960 was worth about \$10,000 today—with his two prizes, Feynman was offering essentially the price of a new car, out of his own pocket. Both prizes were won, but to Feynman's disappointment, nobody else really “got it,” and interest petered out. Since then, there has not been a focused, coordinated effort to follow his pathway, or even a serious study of its feasibility.

Nanotechnology

In 1976 or thereabouts, K. Eric Drexler, MIT undergraduate as Feynman had been in his day, had an inspiration: [\[34\]](#)

“I started thinking seriously about what you could build if you could design protein molecules and other biomolecules. I could see from the literature that there were all these mechanical and electronic widgets inside cells, that these things were synthesized chemically by the cells, ... And I asked myself, Well, what if we could do things like that?”

By 1981 Drexler had worked out enough of an answer to publish a paper in the *Proceedings of the National Academy of the Sciences* on the subject, and to attract a cadre of other MIT students in a Nanotechnology Study Group. By 1986 he and they had worked out enough of the implication of the possibilities to publish *Engines of Creation*, [\[35\]](#) the book which introduced nanotechnology to the wider world.

1959, when Feynman gave his talk, was only six years after Watson and Crick had worked out the structure of DNA. Twenty years later, the notion of being able to understand, and possibly to use, the molecular machinery inside a cell was much better developed.

Drexler’s approach to what he termed nanotechnology and Feynman’s came from completely different directions: Feynman top-down, Drexler bottom-up. But they would get to the same point, as mature technologies: Feynman spoke of the physicist being able to “synthesize absolutely anything;” Drexler called it “complete control of the structure of matter.” It’s important to understand what they really meant by that. A certain amount of common sense, and some perhaps-not-so-common scientific sense, is necessary to interpret those phrases. After all, a stick of dynamite in the process of exploding is an arrangement of atoms, but don’t expect to build such an arrangement by placing one atom at a time. On the other hand, this is no argument against the possibility of a general synthesis capability, reasonably construed.

So let's talk about reasonable things: a hamburger, for example. When you eat a hamburger, no atom is created or destroyed. They are merely rearranged. Some of the carbon atoms are now attached to oxygens, which you exhale as CO_2 . Others make up distasteful fluid and solid excreta—but again, *they are exactly the same atoms as in the hamburger*. If you had the ability simply to rearrange atoms as you wished, supplying energy where necessary, you could transform the various waste products back into a hamburger.

In a sense, we do have a technology that does just that: we use the waste (including the CO_2) to fertilize a field of grain, some of which we keep and some we feed to a cow. We grind them both up into flour and hamburger, respectively, and cook appropriately. That's a lot of resources, time and space; it's surprising hamburgers don't cost \$100! We can imagine a machine that does the same thing directly, without using lifeforms; but it must operate at the same molecular scales and do the same kinds of atomic manipulations that life does.

You cannot make all of the objects that it is possible to describe in a well-appointed machine shop. You can, however, make a wide range of very useful objects—including all the steel parts of the machine shop. You could describe the molecular capabilities of life in much the same way: DNA cannot describe any arrangement of atoms. It can only describe the linear ordering of a string of constituent protein molecules (the amino acids). These, however, turn out to be able to form a vast array of molecular machinery that perform all the basic functions of life. Sometimes unstated but implicit from the beginning was the notion that nanotech would be a self-replicating technology. Heinlein said it explicitly—"reduplicating;" Feynman followed suit, and Drexler started out with the self-reproducing mechanisms of life.

The limits of nanotech are to the limits of the cell's mechanisms as machines are to animals:

Horses and birds DNA and proteins
Trucks and airplanes nanotechnology

Cellular machinery—life—needs water to operate; it is limited to the temperature range between freezing and boiling. It operates slowly (compared to what’s possible at the molecular scale), and is very low-power. Nanotech is not bound by these limitations; it could be much faster, higher-powered, and have a wider operating range than life. Properly appreciated, it appeared to have the potential of incomprehensibly tremendous capabilities. The difference between charcoal and diamond, between sand and computer chips, between diseased and healthy tissue, indeed between the dead and the living, is merely the arrangement of the atoms. No wonder Feynman found himself impressed. In *Nanofuture*, I described Drexler’s vision:

Engines of Creation is a technophile’s dreamscape. It predicts microscopic replicating units able to build skyscraper sized objects to atomic precision. These could be buildings or they could be spaceships. It discusses artificial intelligence and engineering systems able to handle the enormous complexity such designs would require. It speaks of “easy and convenient” space travel, and describes a spacesuit so light and thin that you almost forget you’re wearing it (present-day spacesuits are very awkward and arduous to wear and work in). It mentions cell repair machines and curing “a disease called aging.” It talks about cryonics and resurrecting the frozen.

Feynman had only talked about recording the Britannica on a pinhead, and maybe simplifying the process of complex chemical syntheses. Drexler had gone a long way further in working out what the ability to make “absolutely anything” would actually imply.

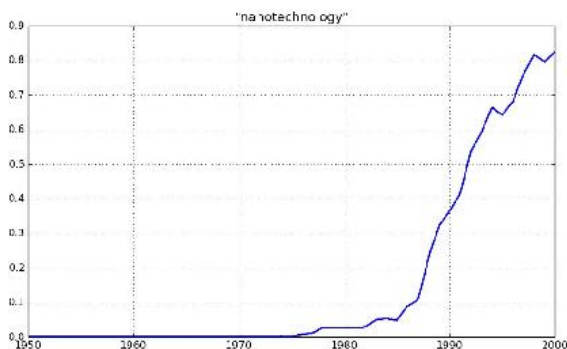
Drexler, who knew he was onto an idea that was revolutionary enough in the first place, remained very carefully and scrupulously inside the boundaries of very conservative engineering estimates in his projections. It didn’t matter, of course; once the concept of nanotech had gotten out, science fiction writers without the technical knowledge (or the scruples—after all, they were writing fiction) took off in all directions. By 1989 there was, for example, a *Star Trek* episode in which “nanites,” very loosely based on Drexler’s assemblers which were in turn based on something like yeast, evolve into an intelligent species in a day or so—and then suddenly

cast aside the slightest hint of being susceptible to evolution and act as a completely coordinated collective entity. Science fiction requires the suspension of disbelief, but that one required abysmal ignorance of ten or so major areas of science and engineering at the same time. It became difficult for someone consuming the popular literature to understand just what was being claimed by those who were doing serious scientific research.

At the same time, though, the excitement inside the technical world was almost palpable. When I founded the Usenet nanotechnology discussion group sci.nanotech in '89, it won approval by the largest vote (and largest margin of yes-to-no votes) any Usenet group ever had. At the inaugural Foresight conference on nanotechnology the same year, more than one of the attendees remarked to me that it felt like being at one of the famous Solvay conferences of the 1930s that were so iconic in the development of modern physics.

As an aside, I will often (but not always) use the term *nanotech* to refer to the original, atomically precise, engineering vision, and *nanotechnology* to refer to the catchall nanoscale science and engineering, mostly materials science, of the type funded under the auspices of the National Nanotechnology Initiative.

It is important to understand how much the thinking, and the excitement, about nanotech in the 80s and 90s owed to Drexler as opposed to Feynman (or Heinlein). *Waldo* had been around for fifty years and *Plenty of Room* for thirty—but no one had done anything about it. After *Engines*, interest took off exponentially:



Google N-grams references to “nanotechnology” take off after Engines of Creation is published.

——Bottom Line——

The power density is large compared to that of macroscale motors: $> 10^{15} \text{W/m}^3$. For comparison, Earth intercepts $\sim 10^{17}$ watts of solar radiation. (Cooling constraints presumably preclude the steady-state operation of a cubic meter of these devices at this power density.)

—K. Eric Drexler, *Nanosystems*

It is difficult, even for someone who has been working with these ideas and numbers for the past couple of decades, to get one's head around the utter raw power potential of real nanotech. What Drexler is saying in this dry passage is that your thousand-horsepower flying car engine fits inside a one millimeter cube. Powering one cubic foot of nanomotors would require more than the entire current level of energy use of the human race planetwide. Nanomotors to power a Kardashev type I civilization, i.e. one that uses an amount of energy equal to all the sunlight that falls upon the Earth (i.e. 5000 times what we actually use in all forms including food), would fit in a 500 square foot apartment (with 8-foot ceiling).

This is why *The Jetsons* is a more realistic depiction of the technology of 2062 than any of the “serious” science fiction or futurism. There simply won't be any motors visible. But that is actually the less important part. The more important part is the effect of moving a self-replicating technology to the nanoscale.

All else being equal, the smaller a machine, the faster it can run. A simple example is the nearly incredible miniaturization in scale and concomitant acceleration in speed that our electronics have undergone during the past half-century. Another familiar example is the wing-flapping speeds of birds and insects, from eagles to mosquitoes. The wings are moving through the air at a similar absolute speed, but since the mosquito has so much less distance in a flap, it can do many more of them in a second.

A part entering a typical factory in the real world may move at an average speed of five feet per second—walking speed—on its journey through the assembly process; and in a typical factory it has hundreds or even thousands

of feet to go from loading dock to finished product. The rapidity with which a factory can process its inputs into outputs is clearly crucial to the value of the factory; a factory that can make 20,000 widgets a week is obviously worth two factories which can only make 10,000.

Imagine that an item of raw material needs to travel a mile through a factory, taking 20 minutes at walking speed. If the factory is scaled down to the size of an average cell, a couple of microns, the corresponding item gets through and into a finished product in a microsecond. In very simplistic terms, this is why humans reproduce in 20 years but *E. Coli* reproduces in 20 minutes.

Reproduction speed has crucial implications for the overall economic growth rate. If your factory costs \$100 million to build, and can produce \$3 million worth of widgets in a year, it will take you 33 years to regain the value of the factory. That level of productivity, 3% per year, has been an average for the Industrial Revolution over the past couple of centuries. (Note that if the widgets are not simply consumed, but re-invested say by improving the capabilities of the factory, the total value will double in 25 years instead of 33, due to the magic of compound interest.) What then if the factory can make a copy of itself in one year, a month, a week, a day? To give you something of a feeling for how vast the productive capability of nanotech would be compared to current industrial technology, an anecdote: At a nanotech conference some years back, Robert Freitas and I were sitting in the lobby of the conference hotel after the day's talks, chatting desultorily of this and that. At one point the question arose how long it would take to replace the entire capital stock of the United States, given a mature nanotechnology. By that we meant rebuild every single building, factory, highway, railroad, bridge, airplane, train, automobile, truck, and ship. At that point, Rob and I had each been thinking, researching, and publishing on the issues and techniques of molecular manufacturing for over a decade, and each of us had his favorite architectures, methods of analysis, and so forth. So we pulled out our notebooks and mulled and calculated for about five minutes. Then we looked up, and answered each other almost in unison, "About a week." [36]

To someone who *hasn't* been studying the capabilities that can be reasonably predicted for nanotech, on the other hand, that sounds fantastic, ludicrous, insane. You are welcome to obtain a copy of *Nanosystems*, a

high-end workstation, a pile of molecular simulation software, and have at it; in ten years or so of hard work you will have a much better grasp of the subject (and be in position to write your own ticket as nanotech begins to show up in the real world, as anyone who had gotten into machine learning a decade ago would be positioned in the AI boom today). But you can get something of a quick and easy sense of it by an analogy.

Nanotech (as distinguished from the “nanotechnology” that is essentially nanoscale surface and materials science) is a digital technology. Once we have machines built to atomically-precise specifications, which can in their turn build more machines to atomically-precise specifications, we will have stepped onto the same escalator that we did in digital information technology.

My computer science mentor at Rutgers in the Eighties had a quip: “To the first approximation, the hardware is free.” What he meant is that the complexity of software required a lot of high-powered, and thus high-priced, brainpower. The complexity, and thus the software, was the bottleneck to increased capability. The complexity of software has grown like gangbusters, but it has, for the past 50 years, followed rather than led the capabilities, sizes and speeds, of the physical computers we run it on. This will be true in spades with nanotech. In computers, the substrate was the computers, running comfortably ahead of your software prowess by virtue of Moore’s Law. In nanotech, the substrate is physics. We have no lack of atoms. The “software” is the design of the machines, self-constructing in digital matter. You can physically rebuild America in a week; how long will it take to design it (much less get construction permits!)?

The power and sophistication of our information processing systems and devices today is fantastic, ludicrous, insane, from the point of view of anyone in the Sixties. Far from stopping, or slowing down, it is still gathering steam today; look at the current surge in “big data,” robotics, and artificial intelligence.

Our physical technology is still in what we might call the Analog Age. The only field in which we are manipulating matter digitally is biotech, where nature has led the way. But within a decade or two the bridge will be crossed. We will begin to make machines that can make “absolutely anything,” in the sense that a printer can print any page or a 3-D printer can

make any shape in its plastic, but in a wide range of engineering materials and with atomic precision. Among the things they will be able to make is more printers. At this point the capabilities of nanotech will begin to take off on a Moore's Law-like curve.

Moore's Law is equivalent to a 60% growth curve. To match this in physical productivity, each machine need only produce a copy of itself, or equivalently do as much work as was involved in building it, in a year and a half. That is for the chip itself; once you factor in the rest of the computer and other constraints and bottlenecks a good estimate for computer power growth over the past 50 years is a rate of about 40%. A fairly conservative nanofactory design reproduces itself in an hour. The same kind of constraints and bottlenecks apply, but we might reasonably expect a 40% growth rate for pure physical manufacturing capability once full-fledged nanotech takes hold.

So compare the capabilities of your iPhone—and its price, size, and power consumption—to that of the IBM 1401, which filled a room, rented for \$20,000 per month (today's dollars), and came fully loaded with 16k bytes of hand-threaded ferrite core memory. That will give you a basis for estimating what physical technology 50 years from now could look like compared to ours—or what ours could have looked like now, if we had listened to Feynman in 1960.

So where is it?

5 The Machiavelli Effect

There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things; because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new. This coolness arises partly from fear of the opponents, who have the laws on their side, and partly from the incredulity of men, who do not readily believe in new things until they have had a long experience of them. Thus it happens that whenever those who are hostile have the opportunity to attack they do it like partisans, whilst the others defend lukewarmly, in such wise that the prince is endangered along with them.

—Nicolo Machiavelli, *The Prince* (1532)

... the member of a mature scientific community is, like the typical character of Orwell's 1984, the victim of a history rewritten by the powers that be.

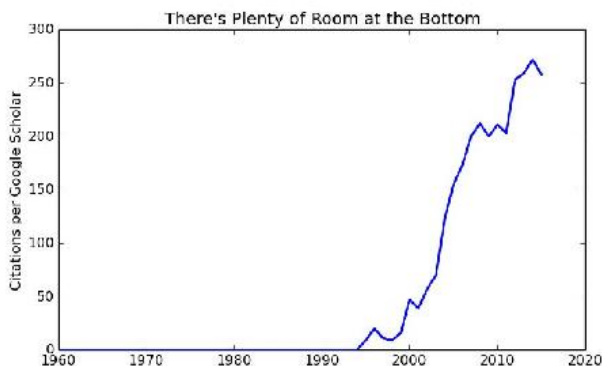
—Thomas Kuhn, *The Structure of Scientific Revolutions*

Medieval stained glass windows are an example of how nanotechnology was used in the pre-modern era.

—NNI website www.nano.gov

The star of nanotechnology rose meteorically in the 1990s. Google Scholar lists no references to Feynman's *Plenty of Room*, which had been published in a Caltech magazine in 1960 and then in a book in 1961, until 1995. Drexler's 1991 MIT dissertation was the very first one explicitly on the subject of "nanotechnology." It was a formidably dense theoretical justification of a relatively small core of the manufacturing capabilities nanotech should enable, and was republished in general release (as

“*Nanosystems*”) in 1992, becoming somewhat improbably a bestseller. The Foresight Institute’s series of technical conferences on nanotechnology grew throughout the decade, attracting the top researchers in related fields. In 1997, for example, our keynote speaker was Richard Smalley, who had just won the Nobel Prize in Chemistry for his discovery of C₆₀, the “buckminsterfullerene” molecule.



Google Scholar references to “Plenty of Room at the Bottom.”

By 2000, the notion of “doing something” about nanotechnology had percolated up the political funding apparatus. President Clinton, standing at Caltech, proposed a National Nanotechnology Initiative. By then, the meme had latched strongly onto Feynman as a point of scientific respectability. Quoth Clinton: [\[37\]](#)

My budget supports a major new National Nanotechnology Initiative, worth \$500 million. Caltech is no stranger to the idea of nanotechnology—the ability to manipulate matter at the atomic and molecular level. More than 40 years ago, Caltech’s own Richard Feynman asked, “What would happen if we could arrange the atoms one by one the way we want them?”

And yet nobody—*nobody*—tried to do what Feynman had proposed. They didn’t even try to do what Drexler had proposed. What happened instead is about as good an example of the pathologies of politically-driven science funding as you can get. Basically, the NNI did not provide new money for a big push into nanotech. It, in effect, took money from a bunch of programs

and researchers in related fields, mostly surface and materials science, stuck a feather of new bureaucracy in its cap, and called it nanotechnology. [38] The researchers in the affected areas reacted in a completely predictable way:

1. They labeled whatever they were already doing, “nanotechnology.”
2. They attacked Drexler’s vision (and by implication, Feynman’s).

This last is exactly the phenomenon that Machiavelli predicted, with insightful correspondence on a number of particulars, five hundred years ago. I call it the Machiavelli Effect; it is useful to have a name because it is distressingly common—perhaps “endemic” would be a better word—in zero-sum science and technology-funding bureaucracy. It needs to be emphasized here that the Machiavelli Effect has nothing to do with any conspiracy. After all, by their lights, existing researchers were simply protecting their own turf. What Machiavelli said was simply an observation of human nature, and the nature of human interaction. It is just an ordinary part of what Kuhn described as the operation of normal science.

What did happen was that the partisan attacks had the effect of endangering the funding of any researcher who attempted to work on anything vaguely like a molecular machine. There was, for example, a really nice and productive program studying nanotech, the real, atomically precise kind, at NASA Ames. [39] It was cancelled. We at the Foresight Institute started having problems getting researchers who had presented interesting, productive work at earlier conferences to come back.

The intellectual content of the attacks was essentially nil. Smalley himself, who for whatever reason found himself in the vanguard of the partisan attackers, reversed his ground on the feasibility of self-replication at the molecular scale more than once. First he agreed with it (in the days of his Foresight keynote), then pooh-poohed it with the implication that nanomechanical engineering was a foolish waste of time, then reversed field again on the grounds that self-replicating nanobots would be too dangerous. [40]

That Machiavelli predicted 500 years ago the actions of the leading lights of the nanoscale science community doesn’t prove anything one way or another about nanotechnology, of course. But it does mean that there should

be less of a presumption that the partisan attacks were based on facts and sound scientific judgement. In Bayesian terms, the prior probability of the attacks was high, independent of the soundness of Drexler's vision. Physical science and engineering are far from the only fields where the Machiavelli Effect can be found. Indeed, for various reasons they are probably the least, rather than the most, affected of the various intellectual elites. A recent paper quotes the great cognitive psychologist George Miller on how hard it was to break the stranglehold of behaviorism on psychology: [\[41\]](#)

The power, the honors, the authority, the textbooks, the money, everything in psychology was owned by the behavioristic school . . . those of us who wanted to be scientific psychologists couldn't really oppose it. You just wouldn't get a job.

But by far the most pathological example of the Machiavelli Effect over the past 50 years was in medicine. This was nothing new: the medical establishment had persecuted Semmelweis and attacked Pasteur over the centuries. But the viciousness with which it attacked Robert Atkins in America and John Yudkin in England for their hypothesis that sugar, not fat, was the primary dietary factor in obesity and heart disease took the phenomenon to an new apotheosis. The attacks had the effect of suppressing honest skepticism of, and research about, the nutritional orthodoxy, but also another effect:

In 1980, after long consultation with some of America's most senior nutrition scientists, the US government issued its first Dietary Guidelines. The guidelines shaped the diets of hundreds of millions of people. Doctors base their advice on them, food companies develop products to comply with them. Their influence extends beyond the US. In 1983, the UK government issued advice that closely followed the American example. ... Consumers dutifully obeyed. We replaced steak and sausages with pasta and rice, butter with margarine and vegetable oils, eggs with muesli, and milk with low-fat milk or orange juice. But instead of becoming healthier, we grew fatter and sicker.

Look at a graph of postwar obesity rates and it becomes clear that something changed after 1980. In the US, the line rises very gradually until, in the early 1980s, it takes off like an aeroplane. Just 12% of Americans were obese in 1950, 15% in 1980, 35% by 2000. In the UK, the line is flat for decades until the mid-1980s, at which point it also turns towards the sky. Only 6% of Britons were obese in 1980. In the next 20 years that figure more than trebled. Today, two thirds of Britons are either obese or overweight, making this the fattest country in the EU. Type 2 diabetes, closely related to obesity, has risen in tandem in both countries. [\[42\]](#)

The orthodoxy is breaking down at long last, but only slowly. The nutritional establishment is fighting tooth and nail to prevent a distinct *mea culpa*. Science advances, funeral by funeral. But in this case it has been the funerals of millions of people dying from diabetes and heart disease as well as the aging scientists who will not change their minds.

It is usually difficult for an interested outsider of a field to distinguish between a case of the Machiavelli Effect and the more normal (and common) case of the experts pointing out that some would-be Galileo is, in fact, simply wrong. By far the textbook knowledge in any given scientific field is, to steal a phrase from AI research, “probably approximately correct.”

The fat controversy provided a rare case where one could test such a question by personal experiment. In 2002 I was approaching 50 and my father had a heart attack. I started to modify my diet in accordance with the conventional wisdom, but by an unlikely coincidence happened to read Gary Taubes’ article in the NYT magazine. [\[43\]](#) That set me doing research, and after discovering that Taubes was at least a reputable science writer with an article in *Science* on the same subject, I decided to try the experiment personally, essentially putting my own life, or at least health, on the line.

The result was, as I wrote to friends sometime later,

... I have more energy. I have more stamina on the tennis court drinking water than I used to guzzling Gatorade. I can walk 10 miles and finish feeling bouncy, whereas before my joints would ache for a

day after walking 5.

I've lost 15 pounds, and body fat percentage has gone from roughly 24 to roughly 17 percent (according to my Tanita resistivity-method scale).

So in this case at least, the consensus of the experts was wrong, and their bureaucratic war on the mavericks was ill-founded and destructive of the overall search for scientific truth. *It is a possibility.*

I discovered, to my amazement, that all through history there had been resistance— and bitter, exaggerated, last-ditch resistance— to every significant technological change that had taken place on earth. Usually the resistance came from those groups who stood to lose influence, status, money as a result of the change. Although they never advanced this as their reason for resisting it. It was always the good of humanity that rested upon their hearts.

—Isaac Asimov

With psychology papers replicating less than 40%, dietary advice reversing after 30y of fatphobia, macroeconomic analysis working worse than astrology, microeconomic papers wrong 40% of the time, the appointment of Bernanke who was less than clueless of the risks, and pharmaceutical trials replicating only 1/5th of the time, people are perfectly entitled to rely on their own ancestral instinct and listen to their grandmothers with a better track record than these policymaking goons.

—Nassim Taleb

The Gods of Mars

“Is what he has been telling me true?” I asked her.

“In part, yes,” she answered. “That about the outer valley is true, but what he says of the location of the Temple of Issus in the centre of his country is false. If it is not false—” she hesitated. “Oh it cannot be true, it cannot be true. For if it were true then for countless ages have my people gone to torture and ignominious death at the hands of their cruel enemies, instead of to the beautiful Life Eternal that we have been taught to believe Issus holds for us.”

—Edgar Rice Burroughs, *The Gods of Mars*

In 1910, the Wright brothers offered their original Flyer, the first successful heavier-than-air flying machine, to the Smithsonian Institution. [\[44\]](#) They were turned down, and ultimately donated it to the Science Museum in London, where it stayed until 1948. In the meantime, the Smithsonian exhibited Samuel Langley’s Aerodrome and labeled *it* the first flying machine. Langley had been director of the Smithsonian and had undertaken a major effort at a flying machine contemporaneously with the Wrights’. The tests of the Aerodrome in 1903 had all ended in crashes, but in 1914 the museum lent it to Glenn Curtiss, who modified it and flew it successfully. Curtiss was a competitor of the Wrights, and was keen to break their patent on the airplane. [\[45\]](#) Somewhat surprisingly, while the Wrights had spent about \$1000 of their own money to build the Flyer, Langley had received over \$50,000 in government funding for his failures [\[46\]](#)—the largest public expenditure by the US for scientific research up until that time.

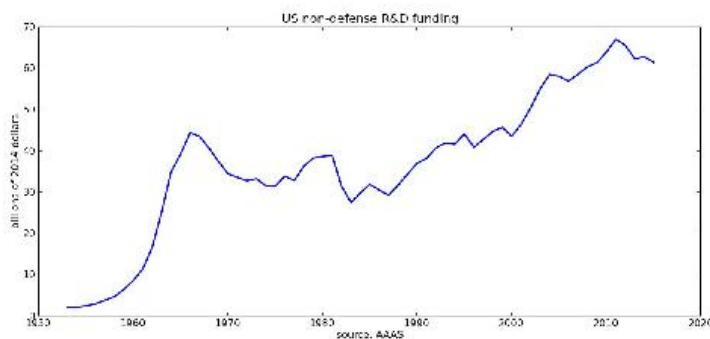
Most everyone who is interested in flying is familiar with this story. Ironic feuds like this are the kind of thing that make up the all too human side of scientific history. But they are generally taken to be the exception to the rule. Among scientists, it is an article of faith that basic research is a public good—that it provides much more overall benefit than it costs, but the benefit is spread so broadly across society that it is in no one’s private interest to fund it. I fully believed this myself, and in fact spent the bulk of

my career doing federally funded scientific research. I got into science in the 1970s, when the government was funding research in space travel, artificial intelligence, nuclear power, even VTOL aircraft.

Various fads in research are funded and defunded all the time. I had started out in Artificial Intelligence in the 70s; in the 80s there was a wave of funding disinterest that researchers referred to as the “AI Winter.” I had basically assumed that the people with the purse strings simply didn’t understand what they were missing. But I don’t think the funding establishment ever turned on AI as viciously as the nanoscience establishment did on true nanotech. It took the complete, knowing, intentional betrayal of the basic concept of nanotech as envisioned by Heinlein, Feynman, and Drexler to make me question the competence of the top-down funding process as capable of advancing the interests of science, technology, and society.

The large amount of funding that Langley had gotten for the Aerodrome had remained the exception rather than the rule in the US up until 1940. Then the Manhattan Project spent \$20 billion (1996 dollars), building more industrial plant than the entire US automotive industry at the time. Defense-related research doesn’t seem to affect economic growth much one way or the other per se, but the remarkable success of the Manhattan project and follow-on aircraft and guided missile research was influential in convincing people, including the futurists of the Sixties, that federal research funding could accelerate scientific progress and economic growth.

The run-up in *non*-defense research spending didn’t happen until the 1960s:



Federal civilian R&D funding in the US. The dramatic rise in the 60s was almost entirely the space program. After the mid-70s, NASA

funding stabilized at roughly \$20 billion.

And yet, as we have seen, the great innovations that made the major quality-of-life improvements came largely *before* 1960: refrigerators, freezers, vacuum cleaners, gas and electric stoves, and washing machines; indoor plumbing, detergent, and deodorants; electric lights; cars, trucks, and buses; tractors and combines; fertilizer; air travel, containerized freight, the vacuum tube and the transistor; the telegraph, telephone, phonograph, movies, radio, and television—and *they were all developed privately*.

It was not just the opinion of a few futurists such as Prehoda, but the firm consensus of the entire economic and scientific establishment, that more federal money for scientific research could only help economic growth. Yet the historical evidence simply does not support the conclusion. England, where the Industrial Revolution had happened and which had experienced the most dramatic rise in personal well-being ever in history, had essentially negligible public support for research throughout the 19th century, while France and Germany, which did have strong public scientific enterprises, never caught up. The United States did catch up, with our GDP per capita exceeding Britain's by the 20th century, but we too were squarely in in *laissez-faire* mode, perhaps even more than Britain. [\[47\]](#)

At the very least, if all the pundits are to be believed, public funding of R&D shouldn't have *hurt*. And yet it coincided with the Great Stagnation, when observers seem to agree that life-changing technological innovations slowed to a crawl.

A survey and analysis performed by the OECD in 2005 found, to their surprise, that while private R&D had a positive 0.26 correlation with economic growth, government funded R&D had a *negative* 0.37 correlation! [\[48\]](#) The authors get fairly mealy-mouthed about it:

The negative results for public R&D are surprising and deserve some qualification. Taken at face value they suggest publicly-performed R&D crowds out resources that could be alternatively used by the private sector, including private R&D. There is some evidence of this effect in studies that have looked in detail at the role of different forms of R&D and the interaction between them. However, there are avenues for more complex effects that regression analysis cannot identify.

The report's authors, and other economists in the field such as Terrence Kealy, apparently gravitate to the assumption that the phenomenon is a crowding-out effect, as clearly happens with government-funded sectors like schools. But my (and the other nanotech researchers') experience showed that there is a non-trivial active backlash as well. I suppose you could call the Machiavelli Effect a "complex effect that regression analysis cannot identify." But I think the explanation is fairly straightforward. Centralized funding of an intellectual elite makes it easier for cadres, cliques, and the politically skilled to gain control of a field, and they by their nature are resistant to new, outside, non-Ptolemaic ideas. The ivory tower has a moat full of crocodiles.

Here are some random chemicals that affect the brain in some random way, which people were using mostly because they felt good at raves, and huh, they seem to treat psychiatric diseases much better than anything produced by some of the smartest people in the world working for decades on ways to treat psychiatric diseases.

—(psychiatrist) Scott Alexander

If it had been up to the NIH to cure polio, we'd have the best iron lungs in the world but we still wouldn't have the Salk vaccine.

—Samuel Broder, Director of the National Cancer Institute

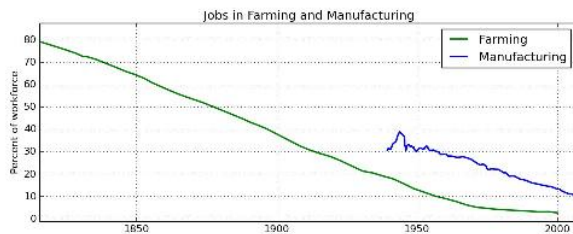
The Inventors of Tomorrow

Our Nation is at risk. Our once unchallenged preeminence in commerce, industry, science, and technological innovation is being overtaken by competitors throughout the world. ... the educational foundations of our society are presently being eroded by a rising tide of mediocrity that threatens our very future as a Nation and a people.

[49]

—Nat. Com. Ex. Ed., *A Nation at Risk* (1983)

Tyler Cowen, in *The Great Stagnation*, proposes that in the 70s we ran out of the “low-hanging fruit” of bright young people coming off the farm and into the university. It is true that there had been a long trend of leaving the farm that slowed in the 70s when virtually everyone had left agriculture:



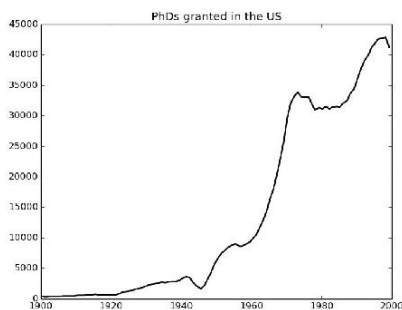
From the nation's founding to about 1970, a steady stream of newly freed-up labor moved from agriculture to the rest of the economy. It is still doing the same from manufacturing. data USDA, BLS via Mark J Perry

Farm jobs in the US as a percent of total have plummeted; there have been more and more young would-have-been farmhands available to do anything else we need. Cowen's argument is that the supply of newly freed-up farmhands dried up in the neighborhood of 1970, due to the fact that the number of people working on farms had gotten so low as to be negligible. But the same thing was still happening with manufacturing workers. The US has very consistently managed to produce more and more manufactured

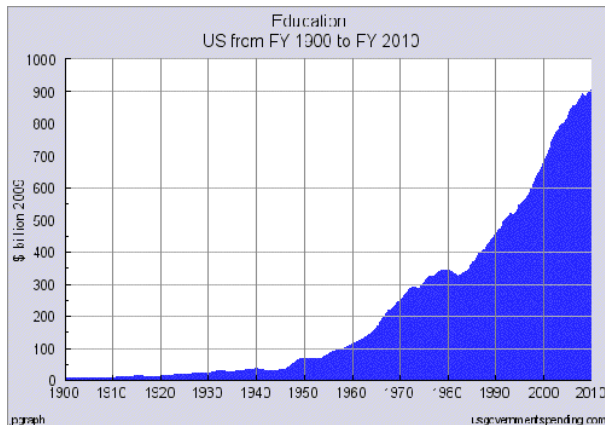
goods with fewer and fewer people, and that means that we have the people available to do whatever else it is we need.

For example, if we took the same proportion of the workforce that was in manufacturing during WWII, plus the people we don't need now in agriculture who were there then, plus the excess size of the armed forces then over now, all into manufacturing (it works out as roughly half the workforce) with today's technological efficiency, we could produce 5 or 6 times as much as we do now. In other words, we have huge headroom in what we could be producing (e.g. flying cars), if only we collectively happened to want to.

A further argument against “we ran out of talent” is that the feminist revolution happened at the same time as the Great Stagnation, roughly doubling the labor pool of smart, capable, young people. And women have in fact taken advantage of education: of the 83,760 PhD's granted in the 1950s, [\[50\]](#) to a fair approximation, all were to men; of 440,497 PhDs awarded from 2000 through 2009, roughly half were to women. [\[51\]](#) Whatever the distribution, there were over five times as many PhDs per year as in the 50s, and 50 times as many as in the early part of the century. Just how many smart young people do you need? Yet over the period, growth slumped and life quit changing for the better. Whatever caused it, it wasn't a lack of smart young talent with college degrees. [\[52\]](#)



PhDs granted in the US. (NSF)



Total government spending on education, in billions of inflation-adjusted 2009 dollars.

The young people are there, and they are being educated in unprecedented numbers. If there is an argument to be made from education rates, it seems likely to run the other way—too many young people are spending too much time in the ivory tower, instead of doing real things in the real world. Kevin Jones, reviewing *TGS* for *Mother Jones*, points out:

But there's a tension here that Tyler doesn't address. Technology grew like gangbusters in the first half of the 20th century, but it wasn't until the second half that education took off. So apparently it's not higher education that's really responsible for dramatic technological growth. But if that's the case, who cares about education?

There seems to be enough evidence to adopt “ivory tower syndrome” as at least a hypothesis. The huge bulge in PhDs in the 20th century seems to match the Great Stagnation pretty well. A proper investigation of it would require more time than we have here (and more economic expertise than your humble narrator can bring to bear), but simply stated, too much education is bad for the economy, and inhibits technological innovation. In November 2005, attending a AAAI symposium, I found myself in casual conversation with one of the other artificial intelligence researchers at the reception. One of the hot topics of conversation in AI circles just then was the DARPA Grand Challenge. The previous month, five autonomous vehicles—self-driving cars and trucks—had successfully completed a

grueling 131.2-mile course in competition for a \$2 million prize offered by DARPA, the defense department's research agency. This was a major advance in the state of the art, since the previous Challenge, held just a year and a half earlier, had been a complete failure, with the best vehicle only managing to go 7.3 miles. [\[53\]](#)

I had remarked as much to my AAI friend, and he demurred. The apparent advance, he insisted, consisted of nothing but clever new ways of combining existing sensory, control, and navigation techniques. That seems to be a fairly common ivory-tower way of seeing things.

But that, of course, is exactly what the vast majority of actual technological progress consists of. And the Grand Challenge results show graphically what kind of a difference it can make in the real world. However much a specialist may recognize all the parts and elements of a new machine from earlier efforts, what the world at large notices is whether or not it works. And in the case of self-driving cars, a major watershed was crossed between March 2004 and October, 2005.

But there was no Clever New Trick that would have excited an academic, *nothing even that an active AI researcher recognized as an advance*. Academia is much more concerned with “mind candy,” intellectual tricks that impress you with the intelligence of whoever thought them up, as contrasted with mundane techniques that just happen to work and do something useful.

Students today are so ignorant that it's hard to accept how ignorant they are. It's hard to grasp that [the student] you're talking to, who is bright, articulate, interested, doesn't know who Beethoven was. Looking back at the history of the 20th Century, just sees a fog. Has the vaguest idea of who Winston Churchill was or why he mattered. No image of Teddy Roosevelt. We have failed.

—(Yale professor) David Gelernter

——Bottom Line——

The demonstration that no possible combination of known substances, known forms of machinery and known forms of force, can be united in a practical machine by which man shall fly long distances through the air, seems to the writer as complete as it is possible for the demonstration of any physical fact to be.

—Simon Newcomb (1906)

The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from transformation of these atoms is talking moonshine.

—Sir Ernest Rutherford (1933)

Inside was a large, shadowy hall, in which bulked a row of tall, square blocks of apparatus. They were, obviously, televisor instruments. Each had a square screen, a microphone grating, and beneath that a panel of control switches, pointer dials, and other less identifiable instruments.

Kenniston found and opened a service panel in the back of one. Brief examination of the tangled apparatus inside discouraged him badly.

“They were televisor communication instruments, yes. But the principles on which they worked are baffling. They didn’t even use vacuum tubes—they’d apparently got beyond the vacuum tube.”

—Edmond Hamilton, *The City at World’s End* (1951)

One large class of technologies which science fiction writers mispredicted were those predicated on some branch of physics the writers didn’t understand. The machines of quantum mechanics—transistors and lasers—are a classic example. (Although Hamilton exercises admirable imagination in positing a replacement for vacuum tubes.) Many of the 1950s’ writers didn’t quite understand orbital mechanics: one fairly typical space yarn has

the intrepid adventurers saving fuel on a mission to Saturn by matching orbits with, and then landing on, an asteroid, and then taking off from it when it gets out to Saturn's orbit. [\[54\]](#)

In the classic work of mid-century futurism, *Profiles of the Future*, Arthur C. Clarke listed two major forms of failure risked by technological prognosticators. Clarke sets the tone for his book by spending two full chapters (and much of the Introduction) discussing cases where eminent scientists and pundits declared various technological achievements impossible—achievements which the twentieth century had then promptly proceeded to produce. He argued by implication that similar predicted limits then current might be looked on with justified skepticism. He divided the mispredictions into two categories: the *Failure of Nerve* and the *Failure of the Imagination*.

The Failure of Nerve applies when the facts are known—the science is there, the engineering understood, the pathway clear, and only the details remain to be worked out. But if the result is so far out of commonsense experience, it is all too easy to grasp for spurious reasons that it might be impossible. The classic case of this, of course, was the near-unanimous insistence of the scientific community that heavier-than-air flying machines were impossible, a position that scientists continued to maintain for about five years *after* the Wright brothers' first flight in 1903. Clarke had plenty of experience with this attitude in the case of rocketry. Perhaps the most flagrant case was the famous *New York Times* editorial denying that rockets could work in space:

That Professor Goddard, with his “chair” in Clark College and the countenancing of the Smithsonian Institution, does not know the relation of action and reaction, and of the need to have something better than a vacuum against which to react—to say that would be absurd. Of course he only seems to lack the knowledge ladled out daily in high schools. [\[55\]](#)

It was with tongue firmly in cheek that the *Times* retracted the claim half a century later, as Apollo 11 was doing its midcourse correction on the way to the moon:

Further investigation and experimentation have confirmed the findings of Isaac Newton in the 17th Century and it is now definitely established that a rocket can function in a vacuum as well as in an atmosphere. The Times regrets the error. [\[56\]](#)

The modern example *par excellence* of the Failure of Nerve is nanotech: absolutely standard physics, quantum mechanics, and chemistry predict that certain arrangements of atoms will behave as workable machine parts, and allow us to calculate the performance of machines so built.

It took the world-class genius of Feynman to break through the paradigm of the kind of things our bulk technology could do, and see the astounding capabilities of a technology completely accessible with the known laws of physics. By the time Drexler considered it, the paradigm had been weakened somewhat by the increasing understanding of the workings of the molecular machines inside the cell, but capturing this as a mechanical technology was still outside the envelope.

The Failure of Imagination is, on the other hand, easier to understand and harder to prevent. It is essentially the same as Donald Rumsfeld's "unknown unknowns:" where the thing that is making your prediction wrong simply isn't part of the toolkit of knowledge that you have available. An exemplary case of this was Rutherford's insistence on the impossibility of nuclear power. He was the leading nuclear physicist of his day; indeed, he was the discoverer of the atomic nucleus. Yet he spoke before the discovery of the neutron and of nuclear fission, both unexpected within then existing physics. If the *fin de siecle* pundits had been pooh-poohing transistors and lasers instead of airplanes, we could not fault them to the same degree, because quantum mechanics was not understood—but they would have been wrong just the same.

Failures of the Imagination are much harder to spot, except in retrospect. All one can do is to stack one's own imagination up against the experts', always a perilous proposition. But we can still reasonably call it a failure because we must always keep in mind that there are things we don't know. Someone who had played with a crystal radio set might well have allowed for the possibility of the transistor, not because he had any knowledge of quantum mechanics, but by guessing that, given there was something in the

physics of the solid state *that he didn't understand* that could act as a diode, there might well also be something that could act as a triode.

One of the great tragedies of the latter Twentieth Century, and clearly one of the causes of the Great Stagnation, was the increasing centralization and bureaucratization of science and research funding. This meant that Failures of Nerve and Imagination, which are particularly strong among bureaucrats, instead of merely causing incorrect predictions from pundits, caused resource starvation and active suppression, and became self-fulfilling prophecies. A century ago, all the smart young people had to make their way in the real world, facing all the messy problems of life, work, and production, and invented new and better ways to solve them. Today, all too many of them spend all too much time in the ivory tower, ever more dependent on handouts from the bureaucracy, and spend their time, efforts, and ingenuity inventing better ways to write grant applications. This had begun to happen enough to foresee and worry about by mid-century; Dwight Eisenhower warned in 1961 that

... the free university, historically the fountainhead of free ideas and scientific discovery, has experienced a revolution in the conduct of research. Partly because of the huge costs involved, a government contract becomes virtually a substitute for intellectual curiosity. The prospect of domination of the nation's scholars by Federal employment, project allocations, and the power of money is ever present and is gravely to be regarded. Yet, in holding scientific research and discovery in respect, as we should, we must also be alert to the equal and opposite danger that public policy could itself become the captive of a scientific technological elite.

The amount of scientific knowledge, at least as measured by journal page counts, accumulated in the past half-century has eclipsed all that had previously been discovered by a gigantic margin. According to *Nature*, scientific publishing has a growth rate of about 8%, for a doubling time of 9 years. [\[57\]](#) That would imply that roughly 60 times as many scientific papers have been published since 1962 as were published in all the time before. But it may well be that ivory tower syndrome both enhances

apparent scientific discovery and impedes useful application. Consider an episode where there was something of a natural experiment: [\[58\]](#)

There was an amazing flowering of science in France at the dawn of the nineteenth century. D. S. L. Cardwell writes, “During the years 1790-1825 France had more scientists and technologists of first rank than any other nation ever had over a comparable period of time.” We can mention Carnot, Lavoisier, Laplace, Montgolfier, Dulong, Petit, Biot, Fresnel, Gay-Lussac, Ampere, Savart, Fourier, Coriolis, Cauchy, and Lamarck—and these are just the ones whose names are attached to scientific laws and inventions that have survived to the present.

What’s more, the advancement of science and technology was a well-funded national policy. Sadi Carnot was a graduate of the Ecole Polytechnique, an institution that had no parallel in England or anywhere else at the time. ...

So if you are a technological forecaster, what do you think happened next? What actually happened, of course, is that the Industrial Revolution occurred in Britain, not France. By 1850, Britain had railroads; Britain had steamships; Britain had the leading engine, machine tool, and textile industries in the world.

The US is the acknowledged leader in science and technology; our top research universities are not only among the best, but are the most numerous, of any country. Our public policy dispenses substantial largesse for scientific research. But the effects of ivory tower syndrome are on full display in the Great Stagnation. It was not due to a lack of basic science, nor of technological capability. The trees of knowledge are growing taller than ever, but someone appears to have been spraying paraquat on the low-hanging fruit.

6 Cold Fusion?

The Occurrence of the Impossible

Petrified with astonishment, Richard Seaton stared after the copper steam-bath upon which he had been electrolyzing his solution of “X,” the unknown metal. For as soon as he had removed the beaker the heavy bath had jumped endwise from under his hand as though it were alive. It had flown with terrific speed over the table, smashing apparatus and bottles of chemicals on its way, and was even now disappearing through the open window.

—E. E. “Doc” Smith, *The Skylark of Space*

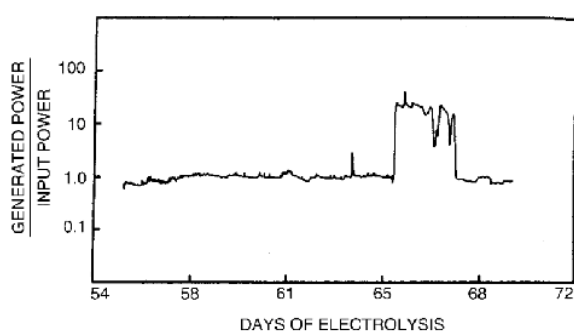
In February 1985, Kevin Ashley, a graduate student in chemistry at the University of Utah, found something of a commotion in room 1113 of the Henry Eyring Building where the electrochemistry labs were. He describes the scene: [\[59\]](#)

The lab was a mess and there was particulate dust in the air. On their lab bench were the remnants of an experiment. The bench was one of those black-top benches that was made of very, very hard material. ... The experiment was near the middle where there was nothing underneath. I was astonished that there was a hole through the thing. The hole was about a foot in diameter. Under the hole was a pretty-good-sized hole in the concrete floor. It may have been as much as four inches deep. ...

Stan and Martin had these looks on their faces as though they were the cat that had just swallowed the canary.

Stan and Martin were, of course, Stanley Pons and Martin Fleischmann, and they were, on that day, extremely lucky men. They thought they were lucky because they had managed to obtain the fusion of deuterium into helium in an electrochemical beaker. They were actually lucky because if they had been correct, the neutron flux and gamma radiation from fusion producing

the amount of energy they had released would have killed every living creature in the building, and rendered it radioactive for years to come. [60] Fleischmann and Pons were, however, certain that they had managed fusion in a bottle, and proceeded to invest \$100,000 of their own money—a quarter million in today’s dollars—in further experimentation over the next 5 years. As well they might: if their experiments had produced a usable power source, they would have revolutionized virtually the entire technological world. They had something that mainstream nuclear engineers could only dream of: a way to convert all the potential energy of deuterium to heat in a ridiculously simple and inexpensive apparatus. Or so they thought.



Trace from a F&P cold fusion experiment from 1985-88: a calorimeter would run for two months producing the same power out as in, then for no apparent reason produce more than ten times as much out for a few days, then just as inexplicably quit.

Four more years of experimentation left them out of money and with not too much more to show in the understanding of the phenomenon, whatever it was, they had discovered. Massive heat releases were rare; it was much more common for nothing at all to happen. The usual case was, after sometimes months of “loading” a palladium electrode with deuterium, it would produce a burst of heat, often ten times more than could be accounted for by the electrolysis current, as measured by calorimetry. There would be no apparent reason for the burst to start, and none for it to stop, as it usually did within a few hours or days. They were electrochemists—Fleischmann was arguably the second foremost physical electrochemist in the world at that point—and this was at the center of their professional

expertise. It seems unlikely that they would have made major, systematic errors in this kind of measurement.

But in 1989, things changed. They needed funding and were trying to get it from the University. The University, of course, was keenly interested in possible patent rights to what might be the major source of energy for the next century. And they—the University administrators as well as Pons and Fleischmann—were given extra reason to believe that they must be causing fusion by the work of Steve Jones, a nuclear physicist at nearby Brigham Young University, for which he had coined the term “cold fusion”. [61]

Jones had coined the term to refer to the process of muon-catalyzed fusion, which is a demonstrated, expected result of perfectly standard physics. In MCF, a muon, which is a subatomic particle similar to but heavier than an electron, forms a kind of pseudo-atom with a deuteron which is like hydrogen but much smaller—so much smaller that it allows another deuteron to get close enough to fuse. Muon-catalyzed cold fusion is completely accepted as real by mainstream nuclear physicists—but it doesn’t produce as much energy as it takes to create the muons. So as an energy source, it’s a dead end.

The UU administrators were worried that they would lose priority for any patents arising from cold fusion, and perhaps Pons and Fleischmann themselves had visions of Nobel Prizes dancing in their heads. Whatever the reason, they were pressured against their better judgement into holding a press conference and rushing a paper into print. Fleischmann later wrote:

I was not at all in favour of the high publicity route adopted by the University of Utah and wanted to delay consideration of publication until September 1990. [62]

The ensuing press conference, and subsequent Preliminary Note published in the Journal of Electroanalytical Chemistry, entitled “*Electrochemically Induced Nuclear Fusion of Deuterium*,” [63] predictably became a media circus and stirred up a firestorm in the scientific world.

Your humble narrator was a young researcher at Rutgers in those days, and I remember the excitement with a certain nostalgia. A friend at Bell Labs called to say that the experiment had been replicated—incorrectly, as it turned out. A friend at Princeton had gotten a copy of the preprint of the

paper, and as he was going out of town, left a much-xeroxed and -faxed copy for me at the desk of the Nassau Inn; I drove down and picked it up at midnight. The closest thing we had to a fusion expert in the computer science department was a numerical analyst who collaborated with some of the hot-fusion physicists at Princeton. I asked him what chance cold fusion had of working, and he quipped “About as good as hot fusion!” Not many days later, I happened to be visiting the physics building, and there was a bunch of people, mostly grad students, trying to reproduce the F&P results. They had set up an electrolytic cell, and they had a neutron detector, and they had surrounded the cell with a wall of lead bricks.

At that point, the incongruity of the whole business struck me. Here were Fleischmann and Pons, sure that they had fusion going on in their cell, running their experiments right out on a lab bench in a plastic tub. And here were the physicists, skeptical that fusion was happening, running theirs behind heavy radiation shielding. (In the following months, I had occasion to repeat the observation as a humorous quip to quite a few people. It seems to have become something of a meme, as I’ve had people repeat it back to me—without attribution, I’m afraid.) What happened next might have been predicted. In a sense, it was predicted in a wierdly ironic way in E. E. Smith’s *Skylark* novel (often credited as the first “space opera”): When Seaton attempts to demonstrate his new discovery to his friends, it doesn’t work, and he is dismissed as being crazy. Then he goes off to develop it on his own, and established industrial interests who want to maintain a monopoly on power generation send thieves to steal his work, hit men to assassinate him and his partner, and finally operatives to abduct his fiancé in a spaceship. The novel is only slightly more melodramatic than the reality.

Pathological Science

It is in the admission of ignorance and the admission of uncertainty that there is a hope for the continuous motion of human beings in some direction that doesn't get confined, permanently blocked, as it has so many times before in various periods in the history of man.

—Richard Feynman

The fact remains that in respectable scientific circles, including the editorial offices of most major journals, the patent office, funding agencies, and tenure committees of academia, cold fusion is leprosy-infested anathema. It remains one of the clearest examples of the Machiavelli Effect in science. A review of the events of 1989 can put the physics community's reaction to cold fusion in context. In January of that year, two months before the March press conference at Utah, Congress had voted that the Superconducting Super Collider was to be built in Waxahachie, Texas. As a result, the high-energy physicists were in the fight of their political lives, indeed a fight they ultimately lost. The reason this was a particularly dangerous time is a perfectly ordinary political phenomenon: an idea that gets a lot of support in the abstract loses luster once the details are known. In this case, congressmen from other states realized that all the hoped-for pork was going to Texas and not to them.

Cold fusion would have been a major embarrassment to high-energy physics. They would have lost not only funding, which in the zero-sum nature of science funding would have gone to cold fusion research, but to some extent the cachet of being the smartest kid on the block in science. So in April, 1989, the Department of Energy convened the Energy Research Advisory Board and formed a committee to investigate cold fusion. The chairman and co-chairman were both from the world of nuclear weapons: John Huizenga was co-discoverer of two transuranic elements isolated in the detritus of the Bikini hydrogen bomb tests, and Norman Ramsey was the liason from Los Alamos who oversaw the assembly of the atom bombs

going to Hiroshima and Nagasaki. This is something of an indicator of the close ties between high-energy physics and high-power politics.

The ERAB committee rushed through a report that was widely regarded as dismissing cold fusion. But on closer inspection, it seems clear that while Ramsey felt his job to be to evaluate cold fusion, Huizenga felt his job to be to discredit it. To that end, Huizenga wrote a popular book debunking it, which gained apparent authority because of his chairmanship of the committee. But the actual committee report is considerably more balanced:

“... even a single short but valid cold fusion period would be revolutionary.

“... it is not possible at this time to state categorically that all the claims for cold fusion have been convincingly either proved or disproved.”

It appears that Ramsey had threatened to resign unless such language were included. The report lists 11 positive, along with 13 negative, experiments for excess heat. And they missed at least one credible positive result for excess heat that occurred midyear at NASA Glenn Research Center. [\[64\]](#) Another of the experiments listed, the one at the Naval Air Warfare Center in China Lake, CA, had not gotten excess heat by the time of the report, and was listed as negative. But they did get positive results within a few months, and the principle investigator, Melvin Miles, is convinced to this day that the phenomenon is real.

The Machiavelli Effect stands out more clearly the closer the critics were to hot-fusion funding. For example, one of the most damning dismissals of Fleischmann and Pons came from MIT's Plasma Fusion Center—who tried a replication of the experiment and reported no excess heat. But Peter Hagelstein, himself an MIT professor, has pointed out that the MIT cells were very poorly designed, with power measurement errors of 40 mW, where Fleischmann and Pons' had an error of 0.1 mW. He wrote

For any unbiased scientist, it should be clear that the Fleischman-Pons calorimetry was far superior to that reported by MIT. Therefore, the MIT calorimetric results cannot be used as a refutation of the Fleischman-Pons reports of anomalous excess energy in Pd/D systems.

[\[65\]](#)

If you look at the raw data from the MIT experiments, they actually do indicate an excess heat release in the deuterium experiment as compared with the light hydrogen control; but it was well within experimental error, so the physicists felt justified in adjusting the data to zero for publication. Given that literally billions of dollars of hot-fusion research dollars were on the line, [\[66\]](#) the plasma physicists' failure to reproduce is less than convincing evidence that Fleischmann and Pons hadn't discovered some real effect, although it certainly wasn't standard D-D high-temperature-style fusion. It's even less convincing given the emotional vituperation ("incompetent boobs," "cult of fervent halfwits") heaped on Fleischmann and Pons by otherwise distinguished but elderly scientists in the process of calling cold fusion impossible.

So by November 1989, the ERAB report was out and the physics community was firmly convinced cold fusion was bunk. But it wasn't until November that Fleischman and Pons published the first paper that gave enough detail that a good-faith replication effort could be attempted. The Machiavelli Effect was on in full force.

Hagelstein, mentioned above, recently gave a presentation about a cold fusion experiment that had been running for 6 months with energy gains of up to 1400 percent (albeit at very low power levels). His talk concluded:

I recently had the experience of working with a large company in the U.S. who was interested in pursuing experiments in this area and helping out. So we put in, we discussed with the technical people at this company of the possibility that they might put in some money for the support of the replication of the Piantelli experiment. So they got the agreement, they got the money, they got it to MIT, and we thought "good, now we can make some progress." However, a very famous physicist at MIT, who is involved in the energy program, found out what we were trying to do, and he cancelled the program. And he called up the vice president of the company and said some things that weren't very polite about the research. And not only did the funding not come and the experiments didn't happen, but my colleagues at the company were very worried about where they're going to work next.

There are two things to note about this: first is that the actual demonstration of the device went on at MIT, starting at a January short course about cold fusion, right out in the open for anyone to check and critique. The second is that the critics resorted instead to backhanded skullduggery and politics. That Machiavelli predicted 500 years ago the actions of the leading lights of the physics community doesn't prove anything one way or another about cold fusion, of course. But it does mean that there should be less of a presumption that the partisan attacks were based on facts and sound scientific judgement. In Bayesian terms, the prior probability of the attacks was high independent of the soundness of the cold fusion reports.

One major problem with the state of cold fusion research today is that while there is a small cadre of smart and careful scientists slowly making small advances, there is also a substantial number of flakes, crackpots, and mountebanks, making outrageous claims—and regularly being discovered to be self-deluded or frauds when serious testing is done on their apparatus. Furthermore, due to the high difficulty of replication, it is all too easy for an honest but inexperienced researcher to fool himself into thinking he has positive results when he doesn't. It wouldn't be at all surprising if the cold fusion literature were at least as unreliable as, say, the biotech literature, where studies have shown that only about 20% of published results could be replicated. [\[67\]](#) The peer-reviewed scientific literature as a whole seems to follow Sturgeon's Law quite well.

Cold fusion is associated in the public mind—and in the minds of quite a few of its more vociferous fans—with perpetual motion, zero point energy, antigravity, UFOs, and heaven only knows what other moonbeams and unicorns. Physicists, for some reason, have come in for more than their share of harassment from crackpots, ranging from flat-earthers to folks with their own versions of relativity or quantum mechanics. And it would require superhuman tolerance and patience, having seen 99 of these crackpots (and they are endless) come in with “limitless free energy” schemes that spring from the total ignorance of all the basic tenets of physics (such as conservation of mass/energy), to see number 100 come in with what seems to be another one of the same, and not instantly file cold fusion with the same squirrel food.

Those who consider themselves the guardians of purity in science, a class that comprises some true scientists and some “science journalists,” like to

use the term “pathological science” for crackpot theories, and they typically include cold fusion in that category. This is at best intellectual laziness and at worst dishonesty; an attempt to discredit something by calling it names. There is vast pathology in science but it is mostly in the biasing and warping of results by the political funding process.

No matter where he travels, one thing will always be the same: man himself. Human nature will not change in the strange outposts of space. There will always be love and hate, courage and fear, and even greed. This is the story of an expedition to a distant world that was brought to the brink of disaster by one man's greed.

—Voiceover narration, *Men Into Space* (1959)

LENR

The only way of discovering the limits of the possible is to venture a little way past them into the impossible.

—Arthur C. Clarke

Arthur C. Clarke wrote that the suppression of cold fusion was “one of the greatest scandals in the history of science.”

Julian Schwinger, Nobel Prize-winning physicist, resigned from the American Physical Society in protest of their treatment of cold fusion and wrote, “The pressure for conformity is enormous. I have experienced it in editors’ rejection of submitted papers, based on venomous criticism of anonymous referees. The replacement of impartial reviewing by censorship will be the death of science.”

At least one other physics Nobel laureate, Brian Josephson, believes that cold fusion should be investigated seriously:

People were too ready to accept the debunkers’ generally ill-informed and fallacious claims, some of the blame for which must be shared by *Nature* through its selective reporting, and its practice of returning papers reporting successful replications to the authors without refereeing them. Typical errors of the debunkers included not realising that materials do not always behave reproducibly, so that it is unsafe to infer, as many did, that failure to reproduce some effect implies that that effect does not exist; and failing to realise that one cannot safely extrapolate from the extremely high temperatures of thermonuclear experiments to the very different conditions in cold fusion experiments, extrapolations frequently used to discredit the phenomenon. [\[68\]](#)

Dennis Bushnell, Chief Scientist of NASA Langley: [\[69\]](#)

The current situation is that we now have over two decades of hundreds of experiments indicating heat and transmutations with

minimal radiation and low energy input. By any rational measure this evidence indicates something real is occurring.

In 1989 Fleischmann was one of the top electrochemists in the world. If he and Pons had published a paper (and got a patent) detailing their apparatus, claiming minor heat amplification (which is what they usually got), and not saying a word about fusion, they would have been much more resistant to attack by the physicists. Instead, the majority of their paper was about attempts to measure fusion products such as gammas and neutrons, an area in which they were not expert and which they did incorrectly.

In doing so, they left themselves open to having high-energy physicists have the say on the scientific validity of their discovery. Physicists attempting electrochemistry, themselves now working outside their own areas of expertise, largely failed to produce any excess heat, and definitely didn't produce the kind of radiation that fusion should have.

At Utah, support for cold fusion was high, and the National Cold Fusion Institute was founded. It ran through \$4.5 million in funding, and even with the direct involvement and support of Fleischmann and Pons, got no results, and closed its doors within a year. For just that extra twist of the ironic knife, the State of Utah wound up paying out 5 times as much money to lawyers as had been spent on the actual physical experiments. [\[70\]](#)

Toyota funded Fleischmann and Pons to the tune of \$40 million the IMRA laboratory in France over the next 5 or so years, and they failed to produce anything useful themselves. Similarly, Japan's MITI spent \$20 million on cold fusion research during the same period, also with no results.

Well, actually not no results at all. There was a slow, groping-in-the-dark kind of improvement in the ability to produce the effect, even though no one could do so reliably on demand. F&P *et al* completed 5 experiments at IMRA: experiment number three produced 150% excess heat, and number four produced 250%—and then number five produced zero. [\[71\]](#)

The experiments were incredibly finicky, maddeningly intermittent, and required enormous attention to detail—and then some luck. Richard Oriani, a leading chemist of hydrogen in metals, is quoted as saying that in his 50-year career, cold fusion experiments were the most difficult he ever performed. In other words, even if you have been enthused by my account here, don't dash out to your garage, grab some heavy water and palladium,

and start bubbling—you're almost certain to fail. But by 2008, there had been over 300 published replications and verifications of cold fusion phenomena by scientists around the world. [72] These are quite varied in scope and thoroughness, in the care and expertise with which they were done, and indeed in the credibility of the results. But only one of them has to be right for the effect to be real.

Much more is now known about the conditions necessary for the phenomenon to occur. Few of the experiments performed in the fever of 1989 came close to loading the palladium sufficiently with deuterium—later results by McKubre at SRI have shown that loading (the ratio of deuterium atoms absorbed into the palladium to the palladium atoms themselves) has to be at least 90%, or nothing happens. Fleischmann and Pons ran experiments for *months* before the palladium was properly loaded. A remarkably small trace of ordinary hydrogen, instead of deuterium, can poison the reaction: simply exposing your heavy water to the air for a brief period will cause it to absorb that much light water—and nothing happens. Either of those factors was enough to have doomed the replication attempt of my physicist friends at Rutgers (the ones with the lead bricks)—their electrolysis cell was a beaker open to the air! And a lot of lab-supply heavy water, meant for other purposes, isn't pure enough in the first place.

Some pieces of palladium work, whereas other pieces produced exactly the same way don't. Palladium is so highly permeable to hydrogen that pieces of the solid metal are used as hydrogen filters. Fleischman found that by far the most reliable palladium samples for the effect to work came from one manufacturer of hydrogen filter palladium (Johnson Matthey). Later researchers, such as Cravens and Storms, have found that only about 4% of samples even from the manufacturing processes that do produce any usable metal, actually work. And it takes a year of careful lab work to winnow out the 4 or so good ones from an apparently identical set of 100.

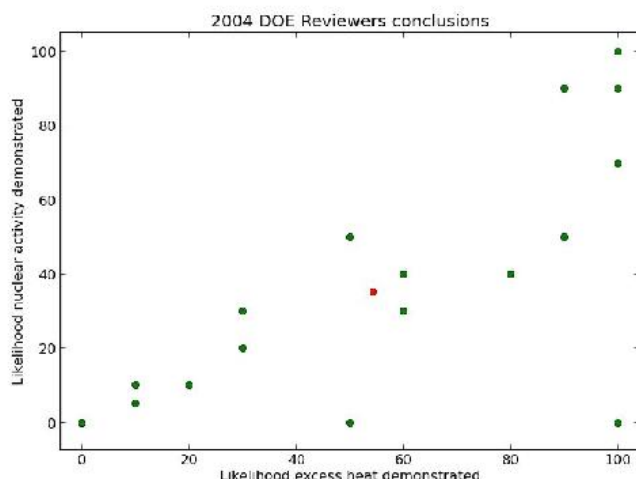
In 2004, the Department of Energy ERAB conducted another review of the status of cold fusion to determine whether to fund experiments in the area. The report was again non-committal, neither strongly supporting or denying the phenomenon. It is more revealing to examine the remarks of the 18 expert reviewers from which the report was compiled. [73] The following quotations perhaps capture the tones of the respective responses:

- The experimental evidence for “cold fusion” is unconvincing.
- The excess heat reported remains unexplained. However, in my opinion, there is no evidence for this being a nuclear physics phenomenon.
- Have the authors provided convincing evidence that the Pd/D system is worthy of continued investigation? The answer is clearly yes.
- This set of articles make a significant case ... that is ... supportive of the claim that excess energy is generated ...
- ... if the DOE receives a proposal in this area ... it should consider it for support as it would any other proposal.
- I find nothing in the articles that I’ve read that convinces me that the new anomalies reported are not experimental artifacts.
- It may well be that future, carefully planned experiments will prove that cold fusion can occur or, more likely in my estimation, cannot occur.
- If the bottom line is that experiments ... give anomalous effects reliably ..., we’ve got the start of science.
- Evidence for excess heat in LENR experiments is compelling and well established. ... The body of work that has resulted from LENR investigations is formidable and worthy of attention of the broader scientific community.
- At this stage, I think the evidence suggests the possibility of such events, [but] cannot be considered conclusive beyond a reasonable doubt ...
- There is strong evidence of nuclear reactions in palladium, and suggestions of reactions in the titanium foil experiments.
- ... intriguing, but not fully convincing.
- I came to the panel meeting with a high degree of skepticism about the “cold fusion” claims ... However, ... there is sufficient evidence to demonstrate that very low energy nuclear reactions can occur in condensed matter at rates that are totally unexpected.
- The rapid heat release from electrolytic cells that is sometimes observed has yet to be understood, but there is no compelling evidence that it is nuclear in origin.
- Have nuclear effects been observed? There is no way to tell ...

- ... there are enough interesting effects suggested by the experiments we have reviewed that further experimental and theoretical investigation is justified ...
- My response [as to whether there is a scientific case for continued efforts] is a weak YES.
- Although much systematic work has been done on the materials properties that produce a successful cell, the reproducibility is still, at best, only 50%.

Note, by the way, that by 2004 the phrase “low energy nuclear reactions,” typically abbreviated LENR, had come to be used as a name for the field, particularly among its advocates. The appellation of “cold fusion” also continued to be used, particularly among critics, a dichotomy which can be observed in the remarks above. It seems likely, though, that if it ever actually turns into a widespread technology, the popular name will probably be “cold fusion,” and there will be a host of more technical terms depending on details of which we currently have no idea.

In a somewhat subjective exercise, I tried to estimate from each DOE reviewer’s remarks what probability he would have assigned to the two questions of whether the results to date had demonstrated excess heat or nuclear phenomena:



An estimate of reviewers’ subjective probability (in percent) for cold fusion phenomena, as an interpretation of review texts. Two points

overlay at 0,0. The red point at approximately 55,35 is the overall average.

While clearly not a resounding affirmation of LENR, this is just as clearly not a dismissal either. The fact that DOE and the journals have given short shrift to new experiments seems more to be a politically driven policy than one reflecting the sober scientific assessment of their own report. (Note that DARPA, the Navy, and NASA have continued to support research at low, sporadic levels of effort.) Perhaps the most reliable tell for the Machiavelli Effect in science is when the establishment scientists seek to prevent experiments that would test the novel claim or hypothesis.

——Bottom Line——

Suppose you make an unexpected scientific discovery: to pick a recent example, that a spider extruding a thread of silk as a parachute gives it an electric charge, which enhances its lifting power. [\[74\]](#) This is cool; it's neat; it's the sort of thing scientists, real ones, live for. But you will not see a press circus and critical firestorm about it. The reason, of course, is that the general public isn't interested: they yawn and say "Nice, but so what?" Not so with cold fusion. The firestorm was ignited with prejudice. The difference, of course, is that the implications of the discovery appeared to be enormous. Part of this perception can be laid at the hands of the hot-fusion people, dating all the way back to Lewis Strauss and "power too cheap to meter." Fusion was always going to be the energy millenium. But of course, the bottom line with nuclear energy, fission or fusion, is the same as the bottom line with "renewables:" for all practical purposes, the fuel is free and the cost of the delivered power is entirely capital cost. Cold fusion promised a capital cost outrageously cheaper than any hitherto proposed fusion (or fission) technology ever dreamed of.

The point of this chapter is not that cold fusion is a dead cert new energy panacea being suppressed by evil government and corporate men in black. I'm a skeptic, albeit an open-minded one—I don't know any physics that makes it work. I feel much more comfortable saying that there is probably something in the physics *that we don't understand* as yet. However, I do see the repression of research, in the same way nanotech research was suppressed. The point is that because of the Machiavelli Effect, *we don't know* whether cold fusion is a possible source of energy. A cold shadow has been thrown into the heart of basic physics. Multiply that by the number of avenues of inquiry that might have led to substantive advancements and progress in the 21st Century, but are almost necessarily not aligned with the interests of the existing funding and science bureaucracy. Nanotech was Failure of Nerve; cold fusion is Failure of the Imagination, transformed from nattering negative punditry to active suppression.

7 Forbidden Fruit

Let's take just one piece of technology that we know was possible—Moulton Taylor's Aerocar—and imagine what might have happened had it “taken off.” It first flew in 1949. We'll never know if Taylor would have been as good a businessman as he was an aircraft designer, but we're exploring what was possible technologically.

The reason that we can imagine this with at least some degree of plausibility is that the the Aerocar was *useful*. Unlike simply owning an airplane, when you bought one you had a car. When you flew somewhere in one, you had a car when you got there. You could do the major part of your route at 110 mph (135 for later models), in an era when, before the Interstate system was built, a road trip was lucky to average a quarter of that speed.

Let's just assume that the Aerocar, and similar competing designs such as Ted Hall's ConvAirCar, had simply followed the same path as the ground car did from 1900, starting in 1950 at the height of post-war pilot registration levels. For the first decade, the analog of the 19-aughts, Aerocars would have remained relatively few in number, owned mostly by rich dilettantes and early-adopter hobbyists. But by 1975, 20% of Americans, i.e. a majority of families, could have owned one. We can plausibly imagine various improvements to have been made along the way: perhaps a quicker and easier way of detaching and reattaching the wings, just as Kettering's self-starter for cars removed one of the more arduous and dangerous aspects of using an automobile starting in 1912. Higher power and higher speeds are almost a given. But we can assume that in a market economy, a substantial amount of the improvement would have gone to increased reliability, usefulness, and easier usability.

So by 1975, there could have been a whole new industry, some non-trivial fraction of the size of the automotive one. Not only would this industry have added to the growth of the GDP directly, but its indirect effects would have been enormous.

Consider that the automotive industry itself had most of its enriching effect by virtue of the things that cars let you do that you couldn't have done otherwise. You didn't just take trips that you would have walked, but faster;

you took trips you never would have made at all. People had homes in places otherwise impossible because they could commute. Businesses otherwise uneconomical could draw customers from a wider geographical base. Vacations; social activities; escape from the claustrophobic confines of small-town life—the automobile delivered all these and more.

One easy way to gauge the impact that a flying-car sector could have had on the economy is to look at the impact the highway system did have. It's estimated to have been responsible for something like a third of all economic growth in the booming, optimistic Fifties. The Interstate system alone is estimated [\[75\]](#) over the latter half of the twentieth century to have added about a trillion (1996) dollars to the economy, building up from nothing when construction started in 1956. It's interesting to note that the same report claims that the annual economic benefit of the interstates peaked at \$38 billion in 1970, and had declined to \$14 billion by the end of the century. (That's direct producer cost reductions; harder-to-measure benefits such as private time savings are thought to be as much again.) In 1986, the section of Interstate 78 across central New Jersey, which leads to New York City via the Holland Tunnel, was finally completed after being held up for decades in the courts. At the time, I owned a house in rural western New Jersey about 15 miles from the highway. The market value of my house essentially doubled, because you could now get to New York in about an hour, where it had taken more like two before. The value of my car, to me but not the market, was also increased in ways hard to measure. That's the kind of increase in value of everything we could have expected from flying cars. People would save time to do the same things, and would be able to do more things. More businesses could exist. A whole new class of businesses, flying car landing strips, would spring up, and other businesses would cluster around them.

The interstate system clearly contributed to the robust 4.1% growth rate up to the beginning of the Great Stagnation, and then began to run out of steam as a source of increased productivity. Flying cars would have been able to finesse that in two ways: first, the practical speed range is much greater, so more places are brought closer together. Second, the highways hit a limit where the cost to build one to less populated places was more than the economic benefit generated. To connect an isolated small town directly to

the high-speed mainstream with the Aerocar, only a much smaller investment in the form of a landing strip would be necessary.

Arguably, then, just this one invention, the Aerocar—more precisely convertibles in general—actually built and proven to work, could by itself have ameliorated the Great Stagnation, if it had gotten started at the right time and developed on a track that brought significant benefits to significant numbers by the timeframe of the seventies. If we had taken that path, given the kind of advances and innovations that have happened in other areas of technology, we would almost certainly have something at least halfway “Jetsonian” by now.

But we didn’t; and the question is why.

Bureaucracy

He has erected a multitude of New Offices, and sent hither swarms of Officers to harrass our people, and eat out their substance.

—Thomas Jefferson, *The unanimous Declaration of the thirteen united States of America*

... vast bureaucracies of civil servants, no longer servants and no longer civil.

—Winston Churchill

In May, 1908, Wilbur Wright arrived in France to make public demonstrations of the Wrights' Flyer. When he opened the shipping crates containing the airplane, however, he was horrified to discover that the contents were a pile of junk. He wrote home with some acerbity, detailing the horrible job of packing that had led to the machine be extensively damaged en route. Luckily for the Wrights' domestic tranquillity, however, it turned out that French customs officials had opened the crates for inspection on the docks at Le Havre, rummaged through the meticulously packed parts, casually tossed them back in, and sealed the crates with a few random nails. All the damage had taken place during the overland trip to Le Mans.

Wilbur, not to be stopped by that kind of misfortune, made friends and enlisted the help of Leon Bollée, an aviation enthusiast who had an automobile factory there, and spent the summer with Bollée's help repairing, essentially rebuilding, the Flyer. The public demonstrations that secured the Wright brothers' worldwide reputation as the true inventors of the airplane finally took place in August.



Bruce Hallock and the Road Wing (courtesy Austin Hallock)

A design similar to Waterman's Arrowbile, but with folding rather than removable wings, was developed privately by Bruce Hallock in the 1950s. Hallock was a pilot, aeronautical engineer and entrepreneur who had seen the Arrowbile as a young boy and been captivated by the tailless design. It seemed to make the most sense for a flying car that there be the least number of parts to add and remove between modes.

To finance his work on the car, which he called the Road-A-Plane, Hallock sold an airplane, a Noorduyn Norseman, which was a single-engine bush plane made in Canada and had been used for light cargo duties by the army in WWII, and then sold as war surplus. The buyers of Hallock's Norseman were a well-established missionary group, the Wycliffe Bible Translators, who specialized in producing high-quality translations of the Bible in native languages and distributing them throughout South America.

Wycliffe was based in Peru, so Hallock flew the Norseman, not without some interesting adventures, to Lima to deliver it.

Sometime later, Hallock was roused out of bed in the middle of the night by a federal marshal and dragged off to jail. The Norseman was apparently a "weapon" (because it had been owned by the Army?) and Hallock was thus guilty of violation of the Neutrality Act. Hallock was tried as a black market arms trafficker. He was in fact guilty, on paper, of failing to file a few forms which would have made the whole transaction completely legitimate.

The jury found him Not Guilty. [\[76\]](#) The Road-A-Plane, at some point renamed the Road Wing, ultimately flew successfully, but Hallock, having had to spend quite a bit on lawyers, never found backers or attempted to manufacture it in quantity. Hallock was essentially subjected, in microcosm,

to the same experience that happened, indeed was still happening at the time, to Pitcairn.



Fulton's Airphibian [National Air and Space Museum]

The other nearly successful flying car of the postwar era, Robert Edison Fulton, Jr's Airphibian, also appears to have run into a regulatory swamp. First tested in 1946, by 1950 its 5 prototypes had logged 100,000 miles in the air and 6000 car/plane conversions. Andrew Glass describes it: [\[77\]](#)

In 1950, Fulton flew his prototype Airphibian to Washington, DC, and landed at National Airport. From there he drove directly to the headquarters of the Civil Aeronautics Administration to claim the first official certification to begin production of a flying car in the United States. ... However, Fulton's financial backers had become discouraged with the seemingly endless expense of meeting government production standards, and they withdrew their support.

Why didn't the Molt Taylor's Aerocar "take off"? It's clear from the postwar spike in licensed pilots that there would have been at least a small market. Perhaps Taylor should have found a partner with more business savvy or money, or licensed or contracted the Aerocar out to some established and experienced manufacturer. But Taylor himself insisted it was government regulation. [\[78\]](#) He was actually in serious negotiations with Ford as late as 1975 to have the Aerocar mass-produced. The monkeywrench was thrown into the negotiations by the FAA and the DOT. Taylor already had an airworthiness certificate for the Aerocar, granted by

the CAA (predecessor of the FAA) after a delay of 7 years from its first flight. He claims that the agencies turned thumbs down on the Aerocar “because everybody would have one, and we couldn’t handle the [air] traffic.”

The agencies may have been instrumental in the suppression of the Aerocar and the others, but by the 70s they would in some sense have been merely standard-bearers for the wave of hostility and suspicion of technology that swept America in the Sixties. Recall the Corvair, a fairly conventional car for most intents and purposes. It was Motor Trend Car of the Year in 1960. In 1965, it was attacked for bad handling by Ralph Nader in *Unsafe at any Speed*, sales collapsed, and it was discontinued by the end of the decade. The Corvair was a mild innovation, and even that only for American drivers. It had a rear-mounted air-cooled engine, like the most successful car model of all time, the VW Beetle. Several other European cars, notably the Porsche 911—hardly a slouch in the handling department—had the same configuration. It required slightly different handling and slightly different maintenance than the standard American car of the period, but was a perfectly safe, reliable car. My uncle had one, and was quite happy with it. Studies done after the fact, by Texas A&M and the NHTSA among others, concluded that the Corvair had if anything slightly superior handling compared to other cars of its period. [\[79\]](#)

But there was just enough unfamiliarity with the Corvair for people to pick a more conventional alternative in the face of the hype of fear and doubt, however factually baseless, spread by Nader’s muckraking. Now compare that with the difference in handling an Aerocar—in the air, that is, although we note with a twinkle of amusement that the Aerocar also had an air-cooled, rear-mounted engine. Small aircraft are not less dangerous in practice than cars. Both have gotten safer over time, but there’s no doubt that there would have been plenty of individual cases of crashes for muckrakers to work from.

One of the things wrought by the demographic shift from, say, 1912 to 1962, was that the US shifted from a majority of workers on farms or in industry, to a fairly small minority. We can’t know for sure, but it seems reasonable that in 1912, when the big uptake in automobiles was getting underway, most people had a family member or friend on a farm or in a factory who was very familiar with machinery. Having a knowledgeable

person accessible meant that you wouldn't simply believe scare stories but ask the real person you knew. But by 1962, this was no longer the case.

Many more people were susceptible to scare stories, because there were so many fewer ripstop threads in the fabric of society.

The Corvair / Nader episode shows that it became possible in the Sixties for scare stories with no basis in fact to become current and widespread, have a significant impact, and indeed to support substantial organizations dedicated to perpetuating them.

Regulation

I would say that we lived in a world in which bits were unregulated and atoms were regulated. If you are starting a computer-software company, that costs maybe \$100,000. But to get a new drug through the FDA, maybe on the order of a billion dollars or so.

—Peter Thiel

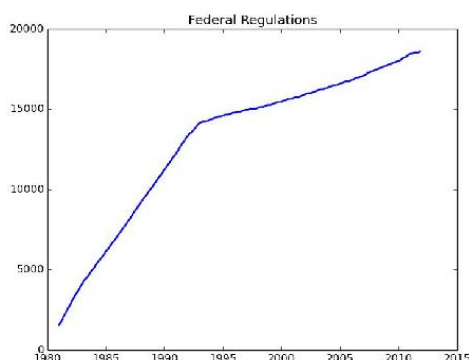
Everyone knows how to obey the laws against robbery. No individual can know how to “obey” laws such as Sarbanes-Oxley (810 pages), the Affordable Care Act (1,024 pages) or Dodd-Frank (2,300 pages).

—Charles Murray

If you want to start an automobile company in this country you need a handful of engineers—and at least 1000 lawyers.

—Arnold Kling

It's pretty clear that the Great Stagnation coincided with the rise in federal regulation. This is from a report commissioned by the Manufacturers Alliance for Productivity and Innovation (MAPI): [\[80\]](#)



Cumulative number of federal regulations on manufacturers.

Administrative law scholars [\[81\]](#) refer to the Nixon administration in the 1970s as the “regulatory explosion.” The 70s saw the passage of the Clean Air Act, the Clean Water Act, National Environmental Policy Act, the creation of OSHA and the EPA, the Consumer Product Safety Commission, and many more. The number of pages in the Federal Register increased by 121 percent under Nixon.

Today, the federal regulatory code is over 175,000 pages long. It’s not light, casual reading either. Here is Federal Air Regulations Part 91, section 1443, paragraph (c):

(c) Notwithstanding paragraph (b)(3) of this section, after maintenance, preventive maintenance, or alterations performed by a repair station certificated under the provisions of part 145 of this chapter, the approval for return to service or log entry required by paragraph (a) of this section may be signed by a person authorized by that repair station.

It’s not about flying. It’s not about aircraft. It’s not about maintenance of aircraft. It’s not about who is qualified to do maintenance. It’s an addendum, with three separate references back into the regulatory corpus, to the rules regarding *who is allowed to do paperwork* about maintenance. The entire F.A.R. / A.I.M., which every airman is responsible for knowing, is 1085 pages long. At least it was in 2013; a new one comes out every year. Economists John Dawson and John Seater recently published a study in the *Journal of Economic Growth*, “Federal Regulation and Aggregate Economic Growth”, [\[82\]](#) that put some hard numbers to these observations. The result is startling: America’s median household income is now \$53,000. If we had simply maintained the amount of regulation we had in 1949 since then, our income would now be \$185,000 per household.

This is only striking because we don’t intuitively understand exponential growth. It represents nothing but the compounded effect of a 2% difference in overall economic growth rate over the intervening 6 decades. In fact it’s somewhat less than Herbert Simon predicted in the Sixties in *The Shape of Automation*. Dawson and Seater basically found that two-percent differences in growth rates are readily observed between countries and correlate robustly with regulatory regimes. (Similarly, a study by Djankov,

McLiesh, and Ramalho in 2006 found that going from the worst to the best quartile of regulatory regimes in the World Bank's Doing Business index was worth a 2.3 percentage point increase in annual GDP growth. [83]) Note that these studies explicitly avoid any consideration of the positive benefits the regulation might have—they are entirely an exercise in calculating the costs. However, it's hard to imagine that regulation has produced so much value that the average American family would readily pay \$132,000 a year for it! The actual benefits of regulation are almost always overestimated. A classic analysis of the 1962 drug laws, for example, found that they cut the rate of introduction of new medical drugs in half while having no measurable effect on average quality. [84] Then there is the phenomenon that economists call "the Peltzman Effect," but is more generally known as "risk compensation." The basic idea is that if you are forced to wear a seatbelt, you will drive a little less carefully and be more likely to get into an accident, though more likely to survive it once you do. But seatbelt advocates tend to ignore the difference in accident rates and calculate the benefits as if the rates didn't change. [85]

The Food, Drug, and Cosmetic Act of 1938 gave the FDA power over all medicine sold in the US. As is typical with such laws, it was in response to a widely publicized disaster. In this case the disaster was the marketing of Elixir Sulfanilamide, which was sulfa, the wonder drug of the 30s, in a liquid form. Unfortunately the formulation, using ethylene glycol, was poisonous and somewhere between 70 and 100 people died of it before doctors understood what was going on and Massengil, the manufacturer, took it off the market and all the existing supplies were tracked down and destroyed.

In October 1938, Merck submitted their new variant of sulfa, Sulfapyridine, to the newly empowered FDA instead of releasing it to doctors.

Sulfapyridine was the first form of sulfa to be effective against lobar pneumonia, in those days a major killer. According to the empowering Act, the FDA had six months to approve the new drug, [86] and as you can probably guess, it took the entire period—which corresponded to the 1938-1939 winter flu season. Once Sulfapyridine did get into the pharmacopia, it was credited with saving 33,000 lives per year. But for the FDA, it would probably have saved 10 or 20 thousand more. [87]

It is commonly believed that regulation of things like medicine and cars is necessary to ensure safety. But life expectancy in the US rose from 47.3 to 68.2 in the first half of the 20th century, an increase of over 30 percent; but in the latter half, the age of regulation, only from 68.2 to 76.8, just 11 percent.

The US government itself estimates that the total cost of regulation in the US is nearing two trillion a year—\$1.75 trillion in 2008. [\[88\]](#) The direct costs were \$15,586 per household per year. This is considerably higher than it has been over the course of the Great Stagnation, and again it ignores benefits. It is easy to believe a two percent reduction going back to the Sixties. But by now it appears to be over ten percent of the economy.

What's more, for the flying car story, the regulatory regime has sat longest and hardest on aviation. The 1931 crash of TWA flight 599, in which Knute Rockne died, was the same kind of widely publicized disaster that sparked an outcry and gave impetus to the regulatory machinery. (Even though, as in the case of Elixir Sulfanilamide, it was private professionals who actually found and fixed the problems.) Anything that goes into a certificated airplane costs ten times what the thing would otherwise. (As a pilot and airplane owner, I have personal experience of this.) It's a lot like the high cost of human medical drugs compared with the very same drugs for veterinary use.

But perhaps the most obvious demonstration that regulation unnecessarily strangles an industry is the rare case where someone actually does the right thing and deregulates. This happened to the commercial air carrier business in the US by way of the Airline Deregulation Act of 1978. It had been noted that in-state airlines operating solely inside Texas and California had fares about half of those for comparable flights in the rest of the country, since interstate airlines were under the tight regulation of the CAB. The 1978 act loosened that significantly: [\[89\]](#)

The United States Airline Deregulation Act of 1978 was ... the first thorough dismantling of a comprehensive system of government control since the Supreme Court declared the National Recovery Act unconstitutional in 1935. ... Between 1976 and 1990 average yields per passenger mile—the average of the fares that passengers actually paid—declined 30 percent in real, inflation-adjusted terms. ... The savings

to travelers have been in the range of \$5 billion to \$10 billion per year. Air travel is unequivocally safer now than it was before deregulation. Accident rates during the twelve-year period from 1979 to 1990 were 20 to 45 percent (depending on the specific measures used) below their average levels in the six or twelve years before deregulation. Moreover, by taking intercity travelers out of cars, the low airfares made possible by deregulation have saved many more lives than the total number lost annually in air crashes.

That was up to 1990. By now, according to the Air Transport Association, prices have fallen in real terms by 44.9%. Air passenger miles have gone from 120 thousand in 1975 to 590 thousand today. [\[90\]](#)

Commercial aviation has long been safer than highway travel. Anything that kept people out of airplanes and in cars raised the accident toll. [\[91\]](#) This is why airline deregulation was such a big win in safety terms: more people flew who would have driven those trips, and been killed on the highways. But the building of airports remains so regulated (not just by the FAA) that only one major new one (KDEN) has been built in all that time.

I have yet to see any even vaguely credible reason why the CAB should have regulated airlines' routes and times to the extent they did in the first place. Note that this was completely separate from the FAA regulations governing every detail of aircraft construction and requiring federal certification of even minor changes of design and equipment; of operations on the ground and in the air (down to and including the requirement that passengers fasten their seatbelts before the airplane moves—F.A.R. §91.107(a)(2)); of the training, licensing, and even work hours of the crew and mechanics; classifications and restrictions of airspace and detailed control of the path of every commercial flight. That's all still there. "Deregulation" just got rid of some of the very worst restrictions on scheduling and routing.

One of the most intimidating aspects of international general aviation flying is the U.S. Customs and Border Protection's electronic notification system known as eAPIS.

How Bad is eAPIS?

It starts with an interface so awful that several entrepreneurial firms

have made successful businesses by offering alternatives. (The most popular, Flashpass, is based in Mexico. Really.) Other lowlights include baffling password rules, nonsensical nomenclature, Microsoft Explorer, and the heavy-handed threat of huge fines if pilots miss their anticipated border crossing times by more than 15 minutes.

—AOPA Pilot magazine (Feb 2015)

Certifying a jet is not the same as certifying a piston-powered airplane, or even a turboprop single. It's a lot more complicated, it takes more people, more money, more money and more money, and a lot more time, too.

—Plane and Pilot magazine

Economic Freedom

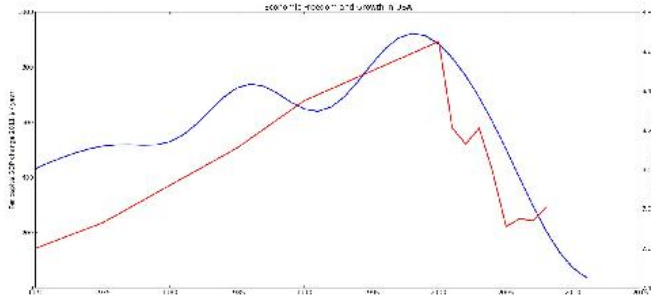
There has grown up in the minds of certain groups in this country the notion that because a man or corporation has made a profit out of the public for a number of years, the government and the courts are charged with the duty of guaranteeing such profit in the future, even in the face of changing circumstances and contrary public interest.

—Robert A. Heinlein, *Life-line*

Regulation, or rather lack thereof, is only one component of overall economic freedom. The basic soundness of a country's institutions: the rule of law, the security of property, and so forth, all critically determine the ability of entrepreneurs to innovate and engage in "creative destruction." It doesn't much matter how many rules there are if the regulators are on the take.

Canada's Fraser Institute publishes an Economic Freedom Index for the countries of the world which takes into account these issues. On a ten-point scale, one point in the index predicts about one to one and a half percent of economic growth. Even at the height of the growth spurt in the Nineties, we had a growth rate two percent below what we could have done with a fully

free economy. Of course, there are no fully free economies; but our average over the period is quite realistically two percent below what the best actual examples achieved. This matches what Dawson and Seater found with a different methodology.



US GDP growth (FredGraph variable USARGDPC_CH1, change, smoothed with a 5-year gaussian) versus the Fraser Institute's economic freedom index for the US.

The average freedom index for the US over the period was 8. If it had been 9, *i.e.* Hong Kong levels, we should be somewhere between one-and-a-half and twice as well off as we are now. Real median household income in the US peaked at about \$57,000 in 2000. [92] If we had had an index of 10 (the top possible score, not attained in the real world) it could have been \$150,000 to \$200,000. Again, this matches Dawson and Seater to within the very loose tolerances that we can expect from any such pluperfect subjunctive analysis.

One of the main ill effects of regulation, at least in the United States, is a significant breakdown of the rule of law. Regulators are not elected and the regulations they promulgate are not subject to any significant check or balance. Last year Congress passed 138 laws; agencies published 2,926 new regulations. Federal courts handled about 95,000 cases; regulatory administrative courts a million.

Ironically it was a Supreme Court decision that was seen at the time as a victory for business and common sense, *Chevron U.S.A., Inc. v. Natural Resources Defense Council* in 1984, that is now generally understood as one of the key enablers of the regulation explosion. The NRDC had sued to

stop a Reagan-era relaxation of some air-quality regulations, and the Court sided with the EPA. [93]

But the result was that the ruling has generally been interpreted as saying that regulators can do anything they want unless it is specifically prohibited in the enabling legislation. If a regulator charges you with a transgression, e.g. OSHA finds that your stair railings are 40 inches high instead of 42, even though there has never been any accident involving them, or that you have bags of ordinary beach sand that are not labelled “Poison,” [94] you don’t get to challenge it in a real court; you must plead your case in the regulator’s own “administrative court.” Because of the all-encompassing breadth and specificity of the regulations and the clueless literality with which they are enforced, it is essentially impossible to run a productive business without breaking some of them. This leaves the individual agents with a free hand to say who they will shut down and who they won’t—a government of men and not of laws.

There are hints of rumblings of “anti-administrativist” sentiment in the higher reaches of the legal profession today. [95] The current system can very easily be interpreted as completely unconstitutional, and there is a growing number of legal scholars who are willing to say so in public, including two Supreme Court justices. We live in interesting times.

Transparency International in 2014 scored the U.S. as a 74 on a scale with 0 as highly corrupt and 100 completely honest. Among actual countries, GDP per capita is strongly correlated with the scale, ranging from \$1000 at 20 (Nigeria) to \$100,000 at 90 (Norway).

Well, for those of you concerned about living down a similar life of privilege, I have a solution for you: start a business. Doing so instantly converted me into a hated abused underclass. Every government agency I work with treats me with a presumption of guilt — when I get called by the California Department of Labor, I am suddenly the young black man in St. Louis called out on the street by an angry and unaccountable cop.

—Warren Meyer

The world of antitrust is reminiscent of Alice's Wonderland: everything seemingly is, yet apparently isn't, simultaneously. It is a world in which competition is lauded as the basic axiom and guiding principle, yet "too much" competition is condemned as "cutthroat." It is a world in which actions designed to limit competition are branded as criminal when taken by businessmen, yet praised as "enlightened" when initiated by the government. It is a world in which the law is so vague that businessmen have no way of knowing whether specific actions will be declared illegal until they hear the judge's verdict — after the fact.

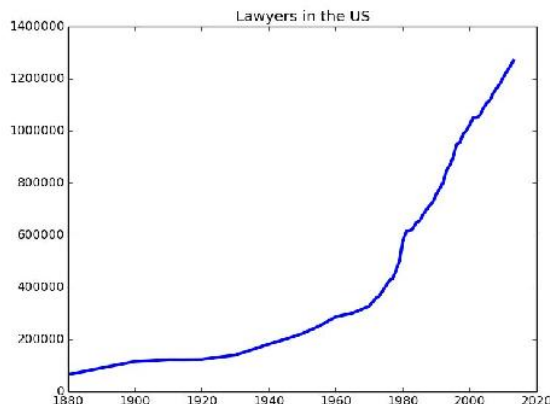
—Alan Greenspan

The Princess and the Pea

In one respect at least the Martians are a happy people; they have no lawyers.

—Edgar Rice Burroughs, *A Princess of Mars*

One major social change in the Seventies that was nominally aimed at safety was the increase in product liability. People would believe any scare story and juries would vote enormous awards for accidents not having any reasonable connection to malfeasance on the part of a manufacturer. The clarion call of so much money had a predictable result; the number of lawyers exploded in the 1970s:



Lawyers in the US (American Bar Association)

This led directly to the collapse of the general aviation industry in the Seventies and Eighties, due essentially entirely to the explosion of product liability lawsuits. From the *Washington Post* in 1983: “The market for two- and four-seater planes, which, until recently, accounted for half of manufacturer revenues, has virtually died.” From a history of Cessna, the company whose name is most synonymous with private planes in the public mind: [\[96\]](#)

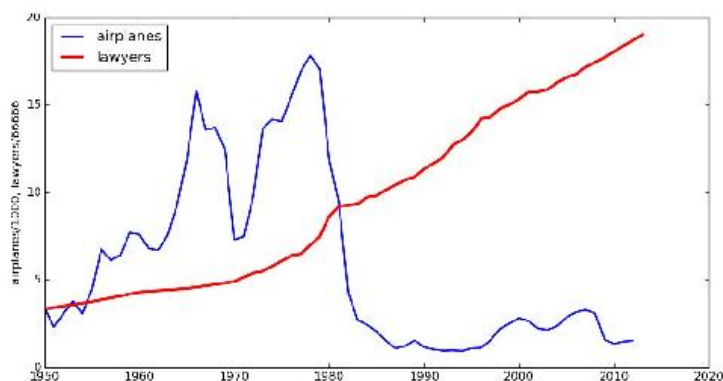
In 1985 Cessna was bought by General Dynamics Corporation and in 1986 production of piston-engine aircraft was discontinued. Over 35,000 172s [\[97\]](#) had been manufactured up until that point. The company cited product liability as the cause for their demise. The corporation’s CEO, Russ Meyer, said that production would resume if a more favorable product liability environment were to develop.

Piper, the Ford to Cessna’s Chevy among private planemakers, went bankrupt in 1991.

The *Concise Encyclopedia of Economics* explains it: [\[98\]](#)

Until the 1980s, property and liability insurance was a small cost of doing business. But the substantial expansion in what legally constitutes liability has greatly increased the cost of liability insurance for personal injuries. The plight of the U.S. private aircraft industry illustrates the extent of these liability costs. Although accident rates for general aviation and for small aircraft declined steadily, liability costs for the industry soared, so that by the 1990s the U.S. private aircraft industry had all but ceased production.

The combined effect of the product liability revolution, the energy crisis, and the general economic recession *circa* 1980 is blatantly obvious on the graph of GA planes shipped.



The fact that it didn't bounce back, as it did after the Energy Crisis dip, is evidence that the effect was a systemic change and not a cyclic downturn. Finally, even Congress managed to note that an entire industry had been destroyed, and in 1994 passed the "General Aviation Revitalization Act," which limited product liability to planes 18 years old and less. This helped a tiny bit—you can see the little bump in aircraft sales that happened in the late Nineties—but the fact remains that a new Cessna Skyhawk cost \$25,000 in 1980 but over \$300,000 today. [\[99\]](#) And then of course the Great Recession destroyed whatever was left of the industry; as I write, only 700 small private airplanes are shipped each year.

General aviation was just one industry. While perhaps a bit more visible and vulnerable than most, no useful and valuable—and thus profitable—industry or occupation escaped the feeding frenzy. Being a highly trusted and respected occupation was no protection. Ask a doctor how much he pays in malpractice liability insurance. [\[100\]](#) According to a study conducted by Tillinghast-Towers Perrin, the cost of the U.S. tort system consumes about two percent of GDP, on average. If we assume this mostly started around 1980 when lawyers skyrocketed and the airplane industry was destroyed, the long-run compound-interest effect on the economy as a whole is startling: without it our economy today would be twice the size it actually is. This is the closest we can come to measuring the effect of taking more than a million of the country's most talented and motivated people and put them to work making arguments and filing briefs, against each other so their efforts mostly cancel out, instead of inventing, developing, and manufacturing things which could have made life better.

If you are looking for perfect safety, you will do well to sit on a fence and watch the birds.

—Wilbur Wright

I don't think that this age is particularly pessimistic when compared with others, but I do think it's somehow gotten better at getting in the way of progress.

—Matt Ridley

Gain of Drones

Repair men reported what seemed to be a sphere of metal, about three feet in diameter, with a four-inch lens in it, floating slowly down the shaft, as though it were some living creature making a careful examination, pausing now and then as its lens swung about like a great single eye.

—Philip Francis Nowlan

In any bureaucracy, the people devoted to the benefit of the bureaucracy itself always get in control and those dedicated to the goals the bureaucracy is supposed to accomplish have less and less influence, and sometimes are eliminated entirely.

—Jerry Pournelle's *Iron Law of Bureaucracy*

Nowlan's "Buck Rogers" novels in the 1920s had one of the earliest descriptions of a long-distance flying drone with video feedback to the operator. (He called them "air balls.") It became technologically feasible to do something like that in roughly the WWII era with full-sized aircraft, but it was both too limited and too expensive for significant use. Drone aircraft of this kind were used extensively in mid-century for target practice, and in the atom bomb tests, but it remained a better option for most other uses to have a human pilot. By far the widest use of radio-controlled aircraft has been by model enthusiasts, purely for hobby use.

In 2012 Congress specifically directed the FAA to produce working rules for drones but the agency has dragged its feet. They claim this is for safety; it is true that idiots flying drones near an airport could produce a hazard for pilots at what is already the most hazardous part of a flight. But in 2015 there were a total of 650 drone sightings from airplanes, although the industry shipped more than 3 million drones. My personal experience as a pilot is that I have seen a grand total of three drones from the air, none anywhere near an area where they would cause a problem. I *own* more drones than that. I see ten times that many large birds, turkey vultures and eagles, every time I fly, and they *are* in dangerous places; just like deer beside the roadway, they will sit along the runway and take to panicked flight just as you are taking off. Many are the times I have taxied up the runway past loitering flocks and taken off on a short field rather than risk their darting up in front of me.

The FAA regulates radio-controlled aircraft but has carved out an exemption for the small hobbyist models. Until recently, most drones were operated under these rules. You must: [\[101\]](#)

- fly below 400 feet AGL (above ground level, as contrasted with sea-level altitude)
- only in daylight
- keep the aircraft within eyeball line-of-sight
- remain clear of manned aircraft operations (stay 5 miles from any airport)
- remain well clear of gatherings of people (notably sporting events)
- not do anything else that could be described as careless or reckless.
- And finally, the model may weigh no more than 55 pounds.

But of course the most important thing about model aircraft—the first sentence on the FAA webpage about them—is “Model aircraft operations are for hobby or recreational purposes only.” Thou shalt not make any money with them.

The same thing, it turns out, is true of ultralights, which can be flown without a pilot’s license, and indeed of flying with a standard private pilot’s license: you are not allowed to make any money. (With one exception: FAR Section 91.321 (a) states that you may receive payment for carrying a

candidate, agent of a candidate, or person traveling on behalf of a candidate, running for Federal, State, or local election.) The FAA, as a general stance and not just with drones, has a deep allergy to people making money with flying machines.

The Mercatus Center's Eli Dourado points out several other ways that the FAA has been instrumental in stifling innovation in aviation:

1. An Uber for Small Planes: If you fly with me in my plane, current rules allow you to pay me for half the fuel but not all of it. But when Flytenow and Airpooler created web-based services to synchronize people wanting to do just this totally legal bit of sharing, the FAA shut them down.
2. Supersonic airliners were always a national politics hobby-horse. After the US failed to produce one, England and France had the only one, the Concorde, and so Congress banned it from landing in the US. The ban was overturned when the ostensible reason, noise over ritzy Long Island suburbs, turned out to be wrong; the Concorde was quieter on approach than conventional airliners. Even so, the FAA continues to ban supersonic flight over land in the US, with no reference to noise, even though modern technology could most likely cut sonic booms in half.
3. Electric sport aircraft: The light sport category of airplanes, specifically intended for joyriding and not cross-country travel, could be a perfect venue for experimentation in full-scale electric flight, since long range is not necessary. But the FAA specifically requires that a light sport aircraft have a single reciprocating engine, if powered (14 CFR 1.1).
4. Passenger multicopter drones: have been built and flown in Germany (Volocopter) and China (Ehang). Don't look for them here any time soon.
5. Air traffic control: Moulton Taylor was right: by far the biggest roadblock to generally usable flying cars is our centralized and extremely antiquated air traffic control system.

But perhaps the most salient example recently and with implications for the possibility of flying cars, is playing out in the latest industry trying to get

off the ground. Amazon, the online marketer, famously proposed to use drones to deliver packages. Not only was this use illegal; the FAA wouldn't even let them *experiment* with drones, and they had to go to Canada to do research and development. [\[102\]](#)

In the real world, the hostility to money probably owes as much to good old ward heeler graft politics as to Marxist ideology. Consider the case of Uber, the ride-hailing smartphone app. (Note that, just as with your airplane, there is no problem with your giving someone a ride in your car for free.) At time of writing, Uber faces 50 federal lawsuits and probably as many again state and local ones. [\[103\]](#) Medallioned taxi cartels in most major cities have reacted to Uber with political (and in some cases physical) attacks, and in many places they have city pols in their pockets. But in protecting their rent-seeking monopolies, they employ a lot of safety and regulation rhetoric. It can be hard to tell where, and how diffuse, the knave/fool boundary is.

The amazing rate of progress in drones in the past ten years or so is probably good reason to believe that something similar might well have happened in flying cars, or could be happening now. The technology certainly appears to be here. The drone industry is on a growth path to triple (i.e. ship 9 million units) in the next 4 years, and add 100,000 jobs and \$82 billion to the economy in the next decade. [\[104\]](#)

One stumbling block is simply that the laws under which you operate a drone are in a state of flux. Beside the FAA's unfinished rulemaking, expected to produce a new set of rules in 2017, the FAA Reauthorization Bill of 2016, currently in the sausage-making process in Congress, may or may not constrain the new rules in various ways. [\[105\]](#)

In 2012, the FAA estimated there would be 30,000 drones in American airspace by 2020. In the first month after mandatory drone registration began in December 2015, 300,000 drones were registered. There are now ten times as many drones as manned aircraft. The FAA now says there will likely be 7 million drones by 2020. Drones are a \$2.6 billion business today, expected to be \$10 billion by 2025. It's a classic case where the technology has done an end run around the technocrats, and it seems fairly obvious that if it had been up to the technocrats to plan it, the drone revolution would not have happened.

——Bottom Line——

So you build your VTOL tilt-wing, and you somehow manage to get it right. It works, and it's reliable, and it burns 5 gallons an hour of car gas... you're a hero. It passes the usual 40 hours for the FAA. It passes the additional 40 hours that a terrified FAA FSDO office has tacked on. So you triumphantly pull it out of the garage and get ready to fly. Here's who shows up at that moment:

- *The Insurance company, who will not insure you to fly it out of your driveway.*
- *The Neighbors, who are suing you for public nuisance, noise, and propeller/rotor blades spinning near their children.*
- *The City Council, being held at gunpoint by the local realtors, who see property values plummeting.*
- *The TV reporters, ready to scare the crap out of everyone within 100 miles for fun and profit (bubonic vermin scum).*
- *The Tax Assessor, who is quickly calculating how to re-classify your home as a profitable airport.*
- *The City Attorney, escorted by the Zoning Commission, who are ready to cite you for operating an un-permitted airport.*
- *The Mayor, who is using this heinous public hazard as a launching platform for media coverage in his run for Governor.*
- *The FAA, (having seen everything above) who has now wisely decided to "amend" the operating limitations on your airworthiness certificate.*
- *Al Sharpton and Jesse Jackson, who are bellowing about how this is a clear example of class warfare and oppression of the downtrodden by the 1%.*

All attempts at humor aside, the pay-off for all the time/money/effort of building a VTOL aircraft may not ever be able to be enjoyed. The technical achievement and triumph is certainly worthy of praise, but there is a tremendous probability that some homebuilder's lifetime of effort will be misplaced and wasted.

—*homebuiltpairplanes.com* user “Victor Bravo”

If we had had in 1900 the regulatory and legal environment that we have now, we would never have gotten the family car; imagine that Ford had gotten sued every time someone steered a Model T into a ditch.

Alternatively, if we had kept the regulatory environment of 1950 (1930 for aircraft) throughout the rest of the century, we would have flying cars today. Over the long run, unchecked regulation destroys the learning curve, prevents innovation, protects and preserves inefficiency, and makes progress run backward. All the reasonable predictions of Golden Age SF and postwar techno-optimism were predicated on the continued growth and affordability of energy. They also presumed an environment of sanity in law and regulation. We had had both throughout the industrial revolution up to the Seventies. The Great Stagnation, looked at under the hood, was really the Great Strangulation.

The crucial question is why things deteriorated so swiftly and all at once just then. Why did American culture shift from the Horatio Alger ideal of hard work producing well-earned success to an attitude more like that of the ancient Greek aristoi or Chinese mandarins who despised tradesmen and the profit motive? Why the explosion in regulation and lawsuits, the emergence of industrial-strength scare-mongering, the collapse of pride and confidence in technology as the way to a better future?

*Thus conscience does make cowards of us all;
And thus the native hue of resolution
Is sicklied o'er with the pale cast of thought,
And enterprises of great pith and moment
With this regard their currents turn awry,
And lose the name of action.*

—Shakespeare, *Hamlet*

8 The Age of Aquarius

The question had come into my mind abruptly: were these creatures fools?

—H. G. Wells, *The Time Machine*

It was this attitude that had made his task so difficult. Decadence. A race on an ages-long decline from vast heights of philosophical and scientific learning. Their last external enemy had been defeated millennia in the past; and through easy forgetfulness and lack of strife, ambition had died. Adventure had become a meaningless word.

—John W Campbell, *The Black Star Passes*

I cannot help fearing that men may reach a point where they look on every new theory as a danger, every innovation as a toilsome trouble, every social advance as a first step toward revolution, and that they may absolutely refuse to move at all for fear of being carried off their feet. The prospect really does frighten me that they may finally become so engrossed in a cowardly love of immediate pleasures that their interest in their own future and in that of their descendants may vanish, and that they will prefer tamely to follow the course of their destiny rather than make a sudden energetic effort necessary to set things right.

—Alexis de Tocqueville

Yet there is no country and no people, I think, who can look forward to the age of leisure and of abundance without a dread. For we have been trained too long to strive and not to enjoy. It is a fearful problem for the ordinary person, with no special talents, to occupy himself, especially if he no longer has roots in the soil or in custom or in the beloved conventions of a traditional society. To judge from the behaviour and the achievements of the wealthy classes to-day in any

quarter of the world, the outlook is very depressing! For these are, so to speak, our advance guard—those who are spying out the promised land for the rest of us and pitching their camp there. For they have most of them failed disastrously, so it seems to me—those who have an independent income but no associations or duties or ties—to solve the problem which has been set them.

—John Maynard Keynes

One of the greatest intellectual achievements of Western civilization, indeed one of the greatest human creations anywhere, anytime, was Isaac Newton's invention of the theory of gravitation and the calculus. Not only could the paths of the planets be understood and predicted, but new, hitherto unseen ones could be deduced and discovered.

In the 1960s, celestial mechanics came to an amazing fruition: one small step out into the universe, guided by that understanding. Our machines and mathematics had taken us to the moon.

But at the same time, the heirs to that bequest of greatness were selling it for a mess of emotional pottage. The Age of Aquarius was dawning. Love, not calculus, would henceforth steer the stars.

In the 1974 movie *Flesh Gordon*, Emperor Wang of the planet Porno turns a "Sex Ray" upon the Earth, causing everyone to abandon whatever they may be doing, strip the clothing from anyone nearby, and indulge in torrid orgies. One is hard pressed to distinguish the movie from the actual Seventies.

It is generally accepted that Western culture—American culture in particular—went through a phase change in the 1960s and 70s. There were the hippies and Woodstock. There was the civil rights movement. There was feminism. There was Earth Day and the rise of the environmental movement.

Arguably, H. G. Wells had predicted it in 1895 in his novella *The Time Machine*:

It seemed to me that I had happened upon humanity on the wane. The ruddy sunset set me thinking of the sunset of mankind. For the first time I began to realize an odd consequence of the social effort in

which we are at present engaged. And yet, come to think, it is a logical consequence enough. Strength is the outcome of need; security sets a premium on feebleness. The work of ameliorating the conditions of life—the true civilizing process that makes life more and more secure—had gone steadily on to a climax. One triumph of a united humanity over Nature had followed another. Things that are now mere dreams had become projects deliberately put in hand and carried forward. And the harvest was what I saw! ...

But with this change in condition comes inevitably adaptations to the change. What, unless biological science is a mass of errors, is the cause of human intelligence and vigour? Hardship and freedom: conditions under which the active, strong, and subtle survive and the weaker go to the wall; conditions that put a premium upon the loyal alliance of capable men, upon self-restraint, patience, and decision. ... For countless years I judged there had been no danger of war or solitary violence, no danger from wild beasts, no wasting disease to require strength of constitution, no need of toil. For such a life, what we should call the weak are as well equipped as the strong, are indeed no longer weak. Better equipped indeed they are, for the strong would be fretted by an energy for which there was no outlet. ... This has ever been the fate of energy in security; it takes to art and to eroticism, and then come languor and decay.

Wells foresaw not only the huge shift away from productive pursuits over the twentieth century, but the sexual revolution and the breakup of the family. The only thing that would have boggled his mind is that it only took one century instead of the 8000 he imagined. It is worth pointing out in passing that Wells' model for the Eloi was the idle rich of the England of his day—the very “advance guard” who Keynes felt had failed disastrously at their task.

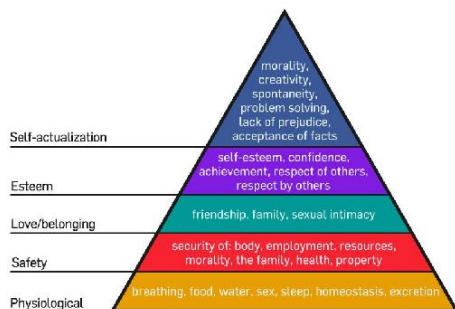
Maslow's Hierarchy

There is no making sense of the world we now inhabit until we confront the yawning chasm that separates our age from the vast bulk of human experience. The mundane, everyday, taken-for-granted circumstances of life in contemporary America's affluent society are, from the perspective of the other side of the chasm, the stuff of flightiest fantasy.

—Brink Lindsey, *The Age of Abundance*

No Utopia can ever give satisfaction to everyone, all the time. As their material conditions improve, men raise their sights and become discontented with power and possessions that once would have seemed beyond their wildest dreams.

—Arthur C. Clarke, *Childhood's End*



Maslow's Hierarchy of needs, according to Wikipedia.

Psychologist Abraham Maslow posited that there is a hierarchy of needs that forms a guide to human motivations. The idea is that the lowest level in the hierarchy that you *don't* have is what you'll spend your time worrying about and working for: The ones below it that you do have, you tend to take for granted; and the ones above are less important in comparison. There has been much written and argued over just which needs are in the hierarchy and in which order, but the notion that there is some such hierarchy

(perhaps different in different people) has proven a robust hypothesis that remains in play seven decades after it was first suggested.

Whatever the particulars, it seems reasonable in the face of the culture shift of the 60s and 70s to suppose that Western culture had essentially succeeded in supplying the needs of the physical layers of the hierarchy, including the security of a well-run society; and that the shift to the Eloi could be thought of as people beginning to take those things—the *Leave It To Beaver* suburban life—for granted, and beginning to spend the bulk of their energy, efforts, and concerns on the love, esteem, and self-actualization levels.

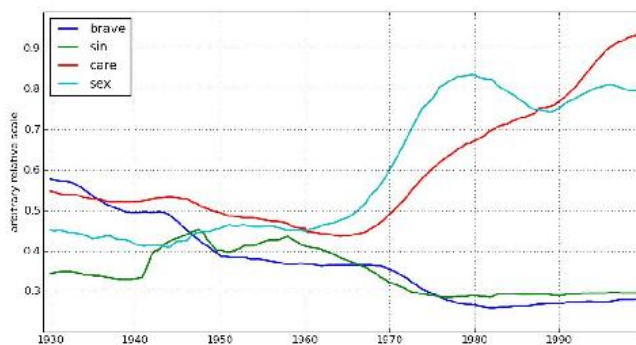
It should be clear that the shift did not by any means happen just in the 60s. Civil rights blossomed then, but we had fought a civil war over the question of slavery a century before. Feminism blossomed then, but there had been suffragettes since the Seneca Falls Convention in 1848. The sexual revolution became general with the Pill, but the Free Love movement actually went back to the 18th century, and was championed by, among others, H. G. Wells himself, in the early 20th. There had been conservationists since Teddy Roosevelt and the founding of the national parks. There had been marxists since Karl Marx and luddites since Ned Ludd. The really interesting question is why all that came to a head at once in the 60s.

By the 60s all these various urges, movements, and social forces were clearly present in society but remained mostly the prerogative of the elites—people rich enough that they already had a lock on the lower levels of the hierarchy. There is a lot of truth to the stereotype seen in the inaugural *Jetsons* episode, where George's boss Cosmo Spacely's wife Stella, whose cognate in 1962 would have been the only one of the characters who actually led a life of complete ease with no real responsibilities, is off picketing the United Planets building with a sign saying "Martians, Go Home." But throughout the 19th and early 20th centuries, the Industrial Revolution had really taken hold and productivity had risen so dramatically that even a lower-middle-class American in 1960 would have been considered substantially well-to-do a century before. The economist Simon Kuznets researched the notion that there is a non-linearity in people's concerns about, *e.g.*, the environment as a function of income. He found

that it inflects at about \$10,000 (per capita per annum). That's just about what the US average income was in the 1960s.

Because this is a book about technology, it is worth pointing out that that is was not only some mystical dollar number that was reached, but the remarkable emancipation of women from the full-time drudgery of housework ("woman's work is never done") accomplished by the labor-saving machines of the 20th Century. By the 60s, housewives had been relieved of something like 75% of the work they had had to do at the turn of the century. It was not a stretch, historically, to imagine the remaining 25% gone by 2062, producing Jane Jetson's button-pushing lifestyle.

We can look at the culture shift in an objective way by looking at words in published material. The "Make Love, Not War" slogan of the 60s, which neatly sums up the Eloi shift from bravery to sensuality, is reflected in a shift in relative occurrence of words in print:



Make care and sex, not sin or brave. (data from Google N-grams)

If we were to try to explain all the different kinds of social and cultural revolutions that flowered in the 60s in terms of different causes, we might have a hard time explaining why they all happened more or less simultaneously: the Sixties was a memetic Cambrian Explosion. But seen as an Eloi shift, they make sense. What was necessary for the flowering of any one of the revolutions was that sufficient people in society had moved up the Maslow hierarchy to the point where esteem and self-actualization became their major concerns, and virtue signalling became more important than real-world results. This fulfilled the precondition for all of them at the same time.

Two other more-or-less exogenous influences on culture during the 60s were the Pill and television. Both were loudly decried at the time, the Pill for its obvious influence on sexual mores, and television for its commercialism. Together with the Eloi shift, they worked a major sea change in the culture; but the single most important factor may well have been the Bomb.

The Proud Tower

We of Arisia will not interfere in person with your proposed conquest of the two galaxies as you have planned it; since the stresses and conflicts involved are necessary—and, I may add, sufficient—to produce the Civilization which must and shall come into being.

—E. E. “Doc” Smith, *First Lensman*

... in Italy for 30 years under the Borgias they had warfare, terror, murder, and bloodshed, but they produced Michelangelo, Leonardo da Vinci, and the Renaissance. In Switzerland they had brotherly love—they had 500 years of democracy and peace, and what did that produce? The cuckoo clock.

—Orson Welles, *The Third Man*

Sooner or later a false belief bumps up against solid reality, usually on a battlefield.

—George Orwell



Rothenburg ob der Tauber, Bavaria, Germany.

If you ever do much travelling in Europe, you are likely to visit preserved medieval cities such as Rothenburg, Germany. One of the features that tourists find so quaint about them is that they are surrounded by walls.

Fewer tourists stand on the wall and imagine what it must have been like to defend it with not much more than an overgrown kitchen knife—or wonder where the attackers were coming from. It turns out, when I asked the Rothenburg guides, that quite often they were just from the next town over. The overwhelmingly important fact about medieval life in Europe was the constant presence of war or the threat of it. The furnace in which Western Civilization was forged came with a very strong evolutionary pressure for moral codes that optimized productivity, efficiency, and hard work, and that emphasized the needs of the polity over those of the individual. (This is hardly an original observation: Both Hume and Montesquieu made it, in different words, in the 1740s!) By 1900, this had produced a life that was obviously much better than it had been in previous centuries, or anywhere else in the existing world. Civilization, with a capital “C,” was a thing, and it was a thing that specifically happened in Europe. We brought it to America largely pre-fabricated.

That vanished in the Postwar World. For all the angst about the Bomb and Mutual Assured Destruction, they drastically changed the nature of warfare. More to the point, they short-circuited the evolutionary process. It was no longer the case that a society which slid into inefficient cultural or governmental practices was likely to be promptly conquered by the baron next door. The nuclear umbrella meant that economic, political, and moral strength of the society was no longer at a premium. The processes of variation proceeded apace, producing a cambrian explosion of Eloi, but natural selection no longer operated. “For such a life, what we should call the weak are as well equipped as the strong, are indeed no longer weak. Better equipped indeed they are, for the strong would be fretted by an energy for which there was no outlet.”

Peter Turchin, the statistical historian whose indicator trends all turned south in the 70s, provides some hard numbers for this story. In his book *Ultrasociety: How 10,000 Years of War Made Humans the Greatest Cooperators on Earth*, he puts it this way:

Here’s how war serves to weed out societies that “go bad.” When discipline, imposed by the need to survive conflict, gets relaxed, societies lose their ability to cooperate. A reactionary catchphrase of the 1970s used to go, “what this generation needs is a war,” a

deplorable sentiment but one that in terms of cultural evolution might sometimes have a germ of cold logic.

War ran out of steam as an effective selection mechanism around mid-20th century. Beginning with Korea, the battles were proxies done at arm's length; the UN forces could (and did) bomb all the industry in North Korea to rubble, but it made no difference since the arms and materiel were coming from the USSR and China. The western world more or less froze the patterns of who was allowed to use what physical force upon whom in place. Then, paradoxically, competence in physical science and engineering was no longer the major factor in political power it had been in the previous centuries.

Turchin continues,

At any rate, there is a pattern that we see recurring throughout history, when a successful empire expands its borders so far that it becomes the biggest kid on the block. When survival is no longer at stake, selfish elites and other special interest groups capture the political agenda. The spirit that “we are all in the same boat” disappears and is replaced by a “winner take all” mentality.

In the US, a major factor in the zeitgeist shift away from seeing our technological accomplishments as a way to a better future was the Vietnam war, which came to be seen as both cruel and useless. It wasn't a “real” war, one that unified people behind a sense of national urgency. Indeed the distrust and disdain for things military it engendered was contagious enough to substantially reverse the admiration and pride Americans had in our technological prowess. Dupont's motto, “Better Things for Better Living...Through Chemistry,” had served it well since 1935. In the pop culture of the Sixties and Seventies, the phrase “better living through chemistry” began to be used sarcastically to describe both recreational drug usage and napalm firebombing. Dupont gave up and dropped the original motto in 1982.

The small polities of the medieval and Renaissance periods had to be reasonably efficient, compared to their neighbors, or be conquered and despoiled. Unfortunately, the impulse of the Progressive Era reformers,

following the visions of Wells (and others) of a “Scientific Socialism,” was to centralize and unify, because that led to visible forms of efficiency. They didn’t realize that the competition they decried as inefficient, whether between firms or states, was the discovery procedure, the dynamic of evolution, the genetic algorithm that is the actual mainspring of innovation and progress.

It is difficult to overstate how much the American experience in World War II shaped both the culture and the institutions not only of the Postwar World (and its expectations for flying cars), but of the great stagnation and the graveyard of dreams. The more or less individualistic and self-reliant culture of the 19th century had been winding down as the frontier filled up, but it gave way with a bang as Americans arose “in their righteous might” to prosecute the war—under a completely centralized bureaucratic government structure. This was not only the military but civilian production planning on an unprecedented scale. We came into the Postwar World with the belief that such a structure *worked*, as it had not only won the war but left the US the pre-eminent industrial power in the world. John Kenneth Galbraith told us that “planning is now a central component of the industrial system.” [\[106\]](#) This is perhaps a major reason that Wells and his Scientific Socialist visions of the future so strongly influenced the American science fiction of the period, all the way up to *Star Trek*.

The economic boom of the 50s and 60s saw America increasingly adopt the model in its economy; it was the age of the national-scale corporation, not only General Motors but General Electric, General Mills, (even General Atomic!), Philip Morris, Nabisco, the Bell System, US Steel, TWA, Pan Am, and the like grew into a set of national institutions (along with the AFL/CIO). There was nostalgia for the self-reliance of the past—westerns dominated entertainment—but the general understanding was that the regulated (and unionized) corporate state was the wave of the future. Television featured The United States Steel Hour, Goodyear Playhouse, Kraft Theatre, The Alcoa Hour, Schlitz Playhouse, The DuPont Show, The Chevy Mystery Show, The Ford Television Theatre, and Bob Hope Presents the Chrysler Theatre—a direct identification with major corporations that would be jarring, if not unthinkable, today.

In retrospect the booming Fifties in America seem to be more a part of a dynamic trajectory than a sustainable steady state. It took the cooperative

“same boat” spirit the “greatest generation” inherited from the war to make the centralized corporate structures work. The Baby Boomers—my generation—split into two cultures which, as far as I can see, not only didn’t agree on values but which fundamentally couldn’t even understand each other. Ask any Boomer what was the greatest, most pivotal event of 1969. Half of us will say the Apollo 11 moon landing. The other half will say Woodstock. Both sets, hearing the other’s opinion, will emit an honestly uncomprehending “Huh!?!?” From the Fifties to the Seventies, the average American followed the lifecycle of Sinclair Lewis’ *Babbitt* from conformity and cooperation to non-conformist rebellion in a search for personal meaning. The corporate state worked with the cooperating, self-sacrificing Greatest Generation. It didn’t work so well with Aquarians.

This is a key point that the Golden Age science fiction writers did in fact get wrong, from which most of the technological missed predictions sprang. From Wells to E. E. “Doc” Smith to Asimov and Heinlein and van Vogt, it had been a central theme of science fiction that not only physical technology but social decision-making would improve, become more scientific, continue to advance along the lines that civilization had done for the past thousand years. It was the post-apocalyptic novels, or retellings of the collapse of the Roman Empire such as *Foundation*, that imagined that science would perish and superstition would rise once again. But in retrospect, it is ease and plenty, the lack of danger and struggle rather than their presence, that appears to engender moral and intellectual decay. If this is true we probably need to rethink just what it is that we want our technology to provide us. The “ridiculous ease” of the Jetsons is fine to lampoon in a cartoon, but real people need challenges commensurate with their capabilities.

... the singular melancholy that the inhabitants of democratic lands often display amid their abundance, and the disgust with life that sometimes seizes them in the midst of an easy and tranquil existence.

—Alexis de Toqueville

The juvenile sea squirt wanders through the sea searching for a suitable rock or hunk of coral to cling to and make its home for life.

For this task, it has a rudimentary nervous system. When it finds its spot and takes root, it doesn't need its brain anymore, so it eats it! It's rather like getting tenure.

—Daniel Dennett

Eloi Agonistes

We are in the midst of a crisis of massive proportions and grave global significance.

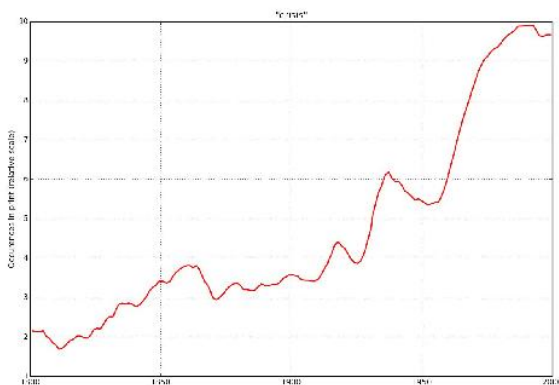
—Martha Nussbaum, *Not for Profit*

For though ours is a godless age, it is the very opposite of irreligious. The true believer is everywhere on the march, and both by converting and antagonizing he is shaping the world in his own image.

—Eric Hoffer, *The True Believer* (1951)

We have all known the loneliness, the emptiness, the plastic isolation of contemporary America. Our forebears came thousands of miles for the promise of a better life. Now there is a new promise. Shall we not seize it? Shall we not be pioneers once more, since luck and fortune have given us a vision of hope?

—Charles Reich, *The Greening of America* (1970)



Eloi Agonistes in one graph: relative occurrences of “crisis” in print. Eloi angst over essentially nothing towers over the Civil War, WWI, the Great Depression, and WWII.

But if you ask the average person of the Western world today, they won't agree that they are the Eloi, living lives of perfect ease in a Utopian garden. They would tell you that they struggled, life was hard, they were doing important, necessary jobs—saving the planet, even.

The next needs up the Maslow hierarchy after safety and comfort are belonging and esteem. The basic human psyche is evolved for the pre-economic tribal environment where esteem came from fulfilling a useful role and being appreciated for it, by others but also by oneself. The human psyche is fairly resistant to the kind of life that Wells described the Eloi as living, a life as a sort of pet or lapdog that was provided for but did nothing useful for others. This is indeed a large part of the narrative power of the story (and its implied criticism of the “idle rich” of its day).

Thus Wells' Eloi are only part of the story of the post-modern Eloi. The people who today take the good life of physical plenty and social stability for granted, after all, need to find self-esteem, the support and respect of their peers. They need to believe that they are changing the world for the good, fighting the forces of evil, saving the planet.

It is the absolute genius of the post-industrial age that we have actually managed to achieve that. It is not as if we have found jobs for most of our talented and motivated people actually making things better—the Great Stagnation story shows that, in fact, they are not doing as good a job of it as their grandfathers did—but a huge segment of our current society *believes* that they are. We have managed to create a society in which a growing majority of people are doing useless, and in many cases counter-productive work, but where we all believe we're doing something necessary and important, that we're making a huge difference for good in the world.

Nor have we subsided into the timid passivity of the Wells' Eloi. We are not “Better equipped indeed, [and not] fretted by an energy for which there was no outlet.” Instead our fretful energy has shifted from conquering the physical world to conquering the world of other people. In this postmodern struggle, objective truth is no longer an advantage; only what you can make someone, including yourself, believe, using emotion instead of evidence.

It is widely unappreciated just how much we are evolved to deceive ourselves. By far one of our most developed sensory and cognitive abilities is to be able to tell when we can trust someone: in an environment of sometimes but not always trustworthy fellow beings this is obviously a

crucial skill and one which would clearly be selected for in evolution. But that is also obviously the basis for a classic evolutionary arms race: the ability to fool someone into thinking you are being honest when you weren't would also be strongly selected for.

It turns out—see for example the work of Rutgers University evolutionary psychologist Robert Trivers, and that of George Mason economist Robin Hanson—that given the way the human mind is constructed, one of the best ways to convince someone you believe something is simply actually to believe it, ignoring all the contradictions between the things you think you know. Computationally, checking the consistency of all the facts in your mental database is expensive—why do it when it is more advantageous not to?

One hardly has to rely on the efforts of these latter-day scientists, of course; it is one of the great themes of literature, ever since there was literature, that one of our greatest flaws as humans was our tendency to self-deception, hypocrisy, and hubris. From Robert Burns to Elmer Gantry, the power to see ourselves as others see us is missing, but is often compensated for by an ability to get others to see us as we see ourselves!

Thus we are built with an almost infinite capacity to believe things because the beliefs are advantageous for us to hold, rather than because they are even remotely related to the truth. Half a millenium ago, we developed science not so much out of a great love of truth, or even because we had begun to develop the tools to discover and propagate it, but because there had arisen a place and a time where it was more advantageous to know the physical facts of nature than not to.

The result of this is that we have major social institutions whose support comes in substantial part from virtue signalling rather than from actual useful results. These are, unsurprisingly, the same ones that are most afflicted by cost disease. In today's America, they include health care, education, and environmental and safety regulation, among others. [\[107\]](#)

There is a psychological effect known as risk homeostasis, which posits that people have a particular level of acceptable perceived risk, and will act so as to keep this level roughly the same. The most common form of this is called risk compensation or the Peltzman Effect, after Sam Peltzman, a University of Chicago economist who studied it in the 70s. (The more general term risk homeostasis was introduced by Gerald J. S. Wilde, of

Queen's University in Ontario, in the 80s.) The effects studied by these and other researchers found that as you introduced noticeable safety features such as seatbelts into cars, for example, people drove faster and less cautiously enough to make the level of perceived risk stay about the same. Wilde noted that after Sweden switched from driving on the left to the right side of the road, accident rates went down as drivers perceived the new conditions as dangerous and drove with more care.

Then over about 18 months, Swedish accident rates climbed right back up to about where they had been before, and stayed there. Once drivers got used to the new conditions, they weren't perceived as dangerous anymore. We can speculate that there is a more general form of risk homeostasis going on in society as a whole. It seems clear that through the Fifties, there was a holdover perception of exogenous military risk from WWII and Korea and the Cold War. But by the end of the Sixties, that had largely disappeared: people quit building backyard fallout shelters, schools quit holding air-raid drills, and so forth. But if people's risk perception level is resistant to change, there are other ways than reckless driving to increase it. One obvious way is simply to start believing scare stories, from Corvairs to DDT to nuclear power to climate change. In other words, the Aquarian Eloi became phobic about everything specifically because we were actually safer, and needed something to worry about.

Instead of saying the SF writers of the Golden Age got it wrong about the advance of social decision-making, I should say that they got it mostly wrong. Asimov, for example, writes in his robot stories about a "Frankenstein Complex" that has people agitating (and legislating) against robots. Shelley's *Frankenstein* itself is one of the foundational works of the sci-fi horror genre and one of the most enduringly popular novels of all time. It follows a long literary tradition from the *Odyssey* to the Brothers Grimm. People like horror stories; they sit around campfires and tell them; Stephen King is an enormously best-selling author; statistics analysis website *FiveThirtyEight* tells us that horror movies are reliably the best investment in Hollywood. The Eloi Agonistes shift doesn't need people to do much different than they have always done; it only requires that they (a) have substantial time to consume what would have been marginal entertainment, (b) an increasing disconnect from the realities of the physical

world, and (c) the Maslow hierarchy need to be doing something *valuable* and *important*.

Unlike a century ago, today for everyone who is working on advancing technological progress, there is someone else who fervently believes that they are saving the planet by stopping them. Has the pace of technological change been impeded? You will remember that we found a remarkably strong correlation between energy intensity and failure of predictions. The more powerful a technology, the easier it is to make it look scary.

Consider a cell phone and a nuclear reactor. There will always be, for any technology, some entrepreneurial Eloi Agonistes attempting to make it appear dangerous and get it banned. In the case of cell phones, for example, they will tell you that the phone causes brain cancer by transmitting through your head. But in the case of the phone, you have personal experience of it, you know many many people who also have experience, and you see that there is no such epidemic as the horror story would imply. But in the case of nuclear power, equally mendacious horror stories are widely believed. The farther from everyday experience something is, the harder to see the truth instead of the horror story.

The Aquarian baby-boomer generation—my generation—grew up in the shadow of the Greatest Generation which had won World War II and had come home and made a paradise of America in the halcyon Fifties, richer and safer than any the world had ever known. We've seen how the human psyche is resistant to the Eloi narrative. My generation was handed the world on a silver platter—but we refused to accept it. So we did something that has happened quite often in religious history: [\[108\]](#) we erected a new God and consigned our fathers to the role of the Devil, so as to be able to look down on them.

San Francisco in the middle sixties was a very special time and place to be a part of. Maybe it meant something. Maybe not, in the long run—but no explanation, no mix of words or music or memories can touch that sense of knowing that you were there and alive in that corner of time and the world. ... There was a fantastic universal sense that whatever we were doing was right, that we were winning. And that, I think, was the handle—that sense of inevitable victory over the forces of Old and Evil.

—Hunter S. Thompson

Dystopias featuring teen-age characters have been a staple of high-school life since “The Lord of the Flies” came out, in 1954. But the genre only really took off in the aftermath of Vietnam and Watergate, when distrust of adult institutions and adult authority flourished ... All of [these books] are characterized by a withering contempt for adults and by an unshakable suspicion of authority.

—Jill Lepore

Only Man is Vile

*What though the spicy breezes
blow soft o'er Ceylon's isle;
Though every prospect pleases,
and only man is vile?*

—Bishop Reginald Heber (1819)

Four legs good, two legs bad!

—George Orwell, *Animal Farm*

The role of DDT in saving half a billion lives did not positively impress everyone, however. On the contrary, many environmentalist leaders were quite upset. As Alexander King, the co-founder of the Club of Rome, put it in 1990, “my chief quarrel with DDT in hindsight is that it has greatly added to the population problem.”

—Robert Zubrin

The strongest of the various forms of Eloi angst is probably Green fundamentalism. Bron Taylor, professor of Religion and Nature at Florida, in his book *“Dark Green Religion,”* quotes John Burroughs, the great naturalist of a century ago: “If we do not go to church so much as did our fathers, we go to the woods much more, and are much more inclined to make a temple of them than they were.” Burroughs was prescient: adherence to and belief in the established religions, notably Christianity, has collapsed to an extent that would have been starkly incredible in his day. In his book *Eaarth* Bill McKibben had written about walking along a creek in the Adirondacks and having it just feel wrong, not because there was any observable change from the natural state but simply because “Merely knowing that we’d begun to alter the climate meant that the water flowing in that creek had a different, lesser meaning.” In one of the more widely quoted passages in *The End of Nature*, he described why that was bad:

Instead of a world where rain had an independent and mysterious existence, the rain had become a subset of human activity. The rain bore a brand; it was a steer, not a deer.

It was bad simply because we had affected it, no further analysis necessary. No detectable change was necessary; anything that humans did that might have had any effect at all was bad by definition. Indeed, it would be evil for us even to *understand* it, making it less “mysterious.” This is the doctrine of Original Sin on steroids. There are plenty of Green fundamentalists who seem to think the human race should simply commit suicide. David Graber, reviewing McKibben, wrote:

I, for one, cannot wish upon either my children or the rest of Earth’s biota a tame planet, a human-managed planet, be it monstrous or—however unlikely—benign. McKibben is a biocentrist, and so am I. We are not interested in the utility of a particular species, or free-flowing river, or ecosystem, to mankind. They have intrinsic value, more value—to me—than another human body, or a billion of them. ... Until such time as *Homo sapiens* should decide to rejoin nature, some of us can only hope for the right virus to come along. [\[109\]](#)

The gospel of the Green fundamentalism was Rachel Carson’s *Silent Spring*, appearing the same year as the *Jetsons* and John Glenn. This was, in the words of one reviewer, a piece of “lyrical nonsense,” which argued that DDT was causing the increase in cancer that was being noted at the time. (The increase was in fact mostly due to smoking, which actually did cause cancer, and to antibiotics, sanitation, generally improving safety and comfort in living and working arrangements—exactly the Eloi transition—which kept people alive long enough for cancer to develop. When DDT was invented in 1939, American life expectancy was 63.7 years; when it was banned in 1971, 71.2.) In mammals, DDT has approximately the same toxicity as aspirin. The CDC did a test giving subjects DDT capsules every day at typical drug doses for 18 months and found no effects. [\[110\]](#) The title of *Silent Spring* was based on the claim that DDT bioaccumulates up the food chain in birds that eat the insects, thinning their shells and impacting their populations. In 1969, a study [\[111\]](#) was published in *Nature* that

appeared to confirm this; but in 1971, the authors retracted it, [\[112\]](#) pointing out that in their original experiment they had fed the quail they studied a diet that was 80% deficient in calcium, and that was the actual cause of the thinned shells.

But the cancer link was the scare hook that gave the book scriptural status—and it was completely wrong. [\[113\]](#) The cancer link tied DDT in the public mind to fallout from the nuclear bomb testing that had been going on throughout the Fifties. That in turn made people think in terms of all the post-Armageddon science fiction, from *On the Beach* to *A Canticle for Liebowitz*, and conflate pretty much any technology with full-fledged nuclear war, and thus the end of the world.

The Green religion has essentially superseded Christianity as the default religion of western civilization, especially in academic circles. Since the sixties it has developed into an apocalyptic nature cult, centered around climate change. Green ideas have become inextricably intertwined with a perfectly reasonable desire to live in a clean, healthy environment and enjoy the natural world. The difference is of course that in the latter case, the human enjoying the natural world is a good thing, but to the fundamentalist Green he and all his works are a bad thing.

The notion that anything human or artificial is necessarily bad (and anything powerful is especially bad) and anything “natural” is good, is a moral postulate. It simply is not a falsifiable statement. Original Sin is a common and powerful memetic psychological hook, and it functions in the Green religion in just the same way it did for the ancient Hebrew scribes. Bishop Heber’s hymn reminds us that this is merely a warmed-over trope from a particularly patronizing period in classical Christianity.

The vast majority of the Eloi Agonistes who “believe in climate change” are not scientists who know anything about the enormously complex Earth climate system. They believe what they do because they have been told it by authority figures; they attach a moral significance to their beliefs; they believe that they are better people because they believe it. Belief in a human-caused climate apocalypse is a shibboleth in intellectual society. They react to skepticism not with careful self-searching reconsideration, but with the scathing inquisitions of heretic-hunters. This is a recipe for religious faith, not scientific knowledge.

Because the issue of climate change is so politically polarized and people are quick to categorize any statement on the subject on political grounds alone, it is incumbent upon any author to be very careful and specific about his position on the subject. My position is this: there is a truly enormous difference between Green activism, which is in its essence religious both in its moral basis and its methods, and the actual scientific study of the Earth's climate and its effect on the human race.

The religious side can be summed up by a recent poll which reported that 39% of Americans believed that there was a greater than 50% chance that climate change would spell the end of humanity. [\[114\]](#) This is an apocalyptic nature cult indeed. But it is mind-bogglingly different from the actual scientific consensus on the subject.

The Intergovernmental Panel on Climate Change (IPCC) is the UN body responsible for collecting and summarizing the known scientific and economic data relating to climate and its effects on the economy. They are the organization that won the Nobel Prize, along with Al Gore, in 2007. They issue periodic Assessment Reports which are essentially the official statement of the scientific consensus on climate change and its economic impacts. The lead-off paragraph of the economic effects section in the current report sums up the issue:

For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers (medium evidence, high agreement). Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change. [\[115\]](#)

The impact of climate change will be small—this is the scientific consensus. *Famine, economic collapse, a sun that cooks us* [\[116\]](#)—this is the religious catechism. A vast gulf is fixed between. Climate change, in the consensus scientific assessment, is only one of many things that will affect the economy a century hence, and a comparatively small one at that. In numerical terms, “the likely combined direct economic effects [of climate change] could reach 0.7 to 2.4 percent of the U.S. gross domestic product

per year by the end of this century.” [\[117\]](#) In other words, a century of climate change *in the worst case* might cost us as much as liability lawyers do now. And that’s in an economy that is expected to be 5 to 10 times richer than ours is—at the median estimates, climate change might cause our great-grandchildren in 2100 to be 7.38 times richer than we are instead of 7.5 times.

Climate change is a hangnail, not a hangman, for the human race. It’s the equivalent of having a growth rate of 2.53% over the rest of the century instead of 2.551%. Anything, including energy conservation, that reduces the growth rate by a single percentage point will harm our grandchildren 50 times as much as climate change. The activists and media have created a hysteria that has absolutely nothing in common with the actual scientific knowledge on the subject. [\[118\]](#)

The two leading human causes of habitat destruction are agriculture and highways—the latter not so much by the land they take up, but by fragmenting ecosystems. [\[119\]](#) One would think that Greens would be particularly keen for nuclear power, the most efficient, concentrated, high-tech factory farms, [\[120\]](#) and for ... flying cars.

If you think your belief is based upon reason, you will support it by argument rather than by persecution, and will abandon it if the argument goes against you. But if your belief is based upon faith, you will realize that argument is useless, and will therefore resort to force either in the form of persecution or by stunting or distorting the minds of the young in what is called “education.”

—Bertrand Russell

“Oh, chief!” Verkan Vall reproached. “You know better than that! How many times have our people got in trouble on other time-lines because they divulged some useful scientific fact that conflicted with the locally revered nonsense? You show me ten men who cherish some religious doctrine or political ideology, and I’ll show you nine men whose minds are utterly impervious to any factual evidence which contradicts their beliefs, and who regard the producer of such evidence as a criminal who ought to be suppressed.”

—H. Beam Piper, *The Last Enemy*

The Central Mystery

The notion that renewable energies and batteries alone will provide all needed energy is fantastical. It is also a grotesque idea, because of the staggering environmental pollution from mining and material disposal, if all energy was derived from renewables and batteries. Worse, tricking the public to accept the fantasy of 100 percent renewables means that, in reality, fossil fuels reign and climate change grows.

—James Hansen

I believe future historians will judge this irrational hatred of nuclear energy as the single greatest reason why greens lost the climate debate. The obvious contradiction between green claims that we face an existential climate crisis and their vehement opposition to nuclear power is what led me and I suspect many other skeptics to question their claims.

—Eric Worrall

I see by your eagerness, and the wonder and hope which your eyes express, my friend, that you expect to be informed of the secret with which I am acquainted; that cannot be: listen patiently until the end of my story, and you will easily perceive why I am reserved upon that subject. I will not lead you on, unguarded and ardent as I then was, to your destruction and infallible misery. Learn from me, if not by my precepts, at least by my example, how dangerous is the acquirement of knowledge, and how much happier that man is who believes his native town to be the world, than he who aspires to become greater than his nature will allow.

—Mary Shelley, *Frankenstein*

“Ergophobia” technically means a neurotic fear of doing work, in an individual. But it comes from the same Greek root as “energy,” and you will

find that physicists use “work” and “energy” to mean the same thing. So I feel justified in using it to refer to the funk our society has gotten into over energy. It is important to note that this had nothing to do with climate change; the crusade against nuclear power preceded the rise of climate concern by two decades. There was even a period in the 70s where the activists were telling us that our cars and industry were emitting so much smoke that they would shade the Earth and precipitate an ice age. The movement as a whole—the activist part, that is—looks very much more like a crusade against energy, using whatever excuses it could find, than an honest reaction to a newly appreciated enhanced greenhouse effect. One of the central mysteries of the green faith is the simultaneous belief that the Earth’s climate is heading for a catastrophe of existential proportions, due entirely to human CO₂ emissions, and yet that completely emission-free nuclear power must be avoided at all costs. But why commit to such a contradiction? Even in a religion one must choose central mysteries with care.

Historically, it was the anti-nuclear weapons movement that morphed into the anti-nuclear power movement. Activists pushed the notion, and many probably believed it themselves, that power plants were giant nuclear bombs waiting to explode at a moments notice and drench the world in fallout. As we have seen, the fact that this was completely untrue didn’t seem to faze the activists in the slightest or impede the growth or influence of the movement.

We have already noted that both environmental and nuclear angst make sense simply as an opposition to energy in whatever form. But why oppose energy on principle? Up until the Sixties, everybody understood how valuable, indeed crucially necessary, it is. It seems likely that the fundamentalist Greens started with the notion that anything human was bad, and ran with the implication that anything that was good for humans was bad. In particular, anything that empowered ordinary people in their multitudes threatened the sanctity of the untouched Earth.

The Green catechism seems lifted out of classic Romantic-era horror novels. Any science, any engineering, the “acquirement of knowledge,” can only lead to “destruction and infallible misery.” We must not aspire to become greater than our nature will allow.

Il est bien malaisé d'ôter à des insensés des chaînes qu'ils révèrent.

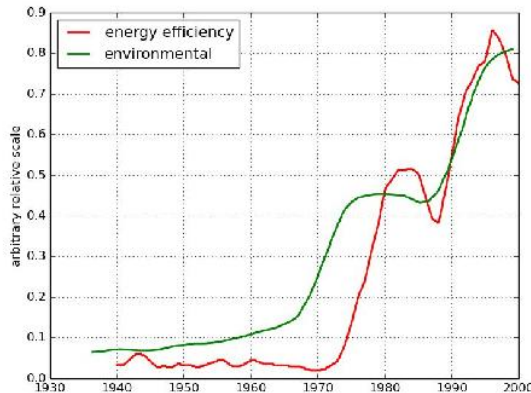
—Voltaire

What We Lost

It is a truism that almost any sect, cult, or religion will legislate its creed into law if it acquires the political power to do so, and will follow it by suppressing opposition, subverting all education to the seize early the minds of the young, and by killing, locking up, or driving underground all heretics.

—Robert A. Heinlein, 1952

It's quite clear that it was in the Seventies that people started worrying about energy. Here's the N-grams chart for “energy efficiency.” It tracks general environmentalism after about a half-decade lag getting started:



The main result of our burgeoning ergophobia was that a lot of inventiveness and engineering resources got shifted from doing new things, and doing things better, to doing the same old things, usually not as well, but using less energy. Up until the Aquarian era, the impact of technology on ordinary life was a continual improvement. Everything from cars to washing machines worked better than the previous models. You got new gadgets that made life easier—televisions, air conditioners, microwaves. That could still be happening; if not for the Great Strangulation, technology

would be nowhere near any limits to improving everyday life. But it feels that way, because nowadays the new model of everything (except electronics) works worse than the previous one.

Take for example the feature, found on some American cars now but much more common in Europe, in which the engine of the car turns off instead of merely idling whenever you come to a stop, say at a traffic light. Then the light turns green, you press the gas pedal, and there is a noticeable pause as the engine cranks up before the car starts moving. This is the sort of thing that automakers are forced into because of particularly stringent fuel efficiency regulations. But over-optimizing for energy efficiency is a game of Whack-a-Mole. Any figure of merit pushed that far will necessarily degrade performance by other criteria. Beside the sluggish performance of the engine-stopping car, consider that it uses its battery and starter motor much more heavily than a conventional car does. That means you have to replace the battery more often, and need a bigger one to start with. The same is true of the starter, which needs to be heavier-duty to have the same operating life, not to mention all the control and sensor electronics to implement the scheme. The whole car is more expensive, needs more maintenance—and doesn't work as well.

The case of diesel cars, mostly in Europe, tells the same story on a bigger scale. There was a push over the past few decades to replace the ordinary gasoline engine in cars with small diesel ones. Diesel is slightly more efficient, using slightly less fuel, especially in larger sizes such as big trucks, trains, and ships. However, especially at smaller sizes, it is dirtier with more toxic exhaust. As a result, European cities from London to Berlin to Rome to Paris have significantly worse air pollution than they would have had with gasoline cars. What's more, the regulations created large incentives for automakers to cheat on emissions testing; Wikipedia puts it:

The VW scandal more generally raised awareness over the high levels of pollution being emitted by diesel vehicles built by a wide range of carmakers, including Volvo, Renault, Mercedes, Jeep, Hyundai, Citroen, BMW, Mazda, Fiat, Ford and Peugeot.

Other examples abound: “Energy Star” dishwashers that hold fewer dishes and take longer to wash them than older models (and as the industry is

currently complaining to the regulators, don't get the dishes clean). Clothes washers with the same problems—modern washers are really excruciatingly slow compared to 20th century ones. Compact fluorescent light bulbs that pause before coming on, give a sickly wan light, and cost ten times the incandescent they replace—and then constitute genuinely hazardous environmentally harmful waste when you do replace them. Remember the Whack-a-Mole principle. Showers that drizzle you with tepid water: the Federal Energy Policy Act of 1992 mandates that “all faucet fixtures manufactured in the United States restrict maximum water flow at or below 2.5 gallons per minute (gpm) at 80 pounds per square inch (psi) of water pressure or 2.2 gpm at 60 psi.” Dinky little cars that come with a high price premium, have no acceleration, no room for your luggage, and you hit your head getting into them. Houses so tightly insulated as to turn naturally-occurring radon into a health hazard. Young men spending their time indoors playing video games, instead of outdoors playing with flying machines. It's not just fast, comfortable cars [\[121\]](#) that get clobbered by ergophobia; it's everything, including other green goals. For example, South Australia is a major leader in so-called renewable energy. As a result, energy costs have gone through the roof. One company, Plastics Granulating Services, saw their power bills go from \$960,000 to \$2,160,000 per year. After operating in the black for 37 years, they are now out of business. Oh yes—what they did was recycle 15% of Australia's low-grade plastic waste stream. [\[122\]](#) And it is not even clear that the push to energy efficiency accomplished much when driven by top-down political fiat. You remember that the Henry Adams Curve had about equal parts of raw energy increase and energy efficiency increase, steadily over the entire Industrial Revolution period. In 1712, Newcomen's engine got less than 3 horsepower-hours of work from a bushel of coal; Watt's in 1769 got 14; Woolf's in 1804 got 28. By 1840, when Adams picks up the thread, the standard was over 60. The average annual efficiency improvement over the Industrial Revolution—Adams' “the ton of coal yielded three or four times as much power in 1900 as in 1840”—was 2%. Over the period of the federal regulatory CAFE standards listed by Wikipedia, [\[123\]](#) the annual improvement for passenger cars was about 1.5%.

Of course, there's nothing wrong with using less energy, *ceteris paribus*—but of course, other things are not equal. The talent, innovation, and

resources that would have gone into technological advance and significant improvement to our way of life were sacrificed to the Green god. Similarly in all the crusades of the Eloi Agonistes—*especially* the ones which did significant good in early days, or are aimed at some incontrovertibly crucial end, such as preventing nuclear war. *The religious fervor of the crusade is necessary to satisfy the higher levels of the Maslow Hierarchy.* But the very fervency of the jihad makes it extremely susceptible to noble cause corruption, the abandonment of conscience and common sense in the furtherance of the Holy Cause. In the early 70s, right after the founding of Earth Day on Vladimir Lenin's 100th birthday, left-wing activists committed more than five bombings *per day* in the US for a sustained period of more than a year and a half. [\[124\]](#) And, I suspect, fervently believed they were doing good, saving the planet. Back in the Fifties, Eric Hoffer had noted that “Every great cause begins as a movement, becomes a business, and eventually degenerates into a racket.” Dr. Patrick Moore, co-founder of Greenpeace, wrote:

The organization I co-founded has become a monster. When I was a member of its central committee in the early days, we campaigned – usually with success – on genuine environmental issues such as atmospheric nuclear tests, whaling and seal-clubbing. When Greenpeace turned anti-science by campaigning against chlorine (imagine the sheer stupidity of campaigning against one of the elements in the periodic table), I decided that it had lost its purpose and that, having achieved its original objectives, had turned to extremism to try to justify its continued existence.

In some cases, notably the production of energy, the Eloi stand as impassioned opponents to beneficial, indeed desperately needed, technological advances. In others, however, and this is probably just as great an overall effect, simply the diversion of so many of the most talented and motivated members of the last several generations from productive pursuits to expensive virtue signaling is one of the main causes of the technological slowdown and the Great Stagnation. If your neighbor is Saving the Planet, it seems somehow less valuable merely to keep clean water running in the mains, or fill potholes, or build bridges. Eloi Agonistes

have stolen the respect and gratitude that the people who are actually doing valuable work should be getting.

In those days we still did homework instead of rioting.

—Keith Laumer

The Baby Boom generation has let the country down in many ways; the systematic neglect of the basic and necessary services of national life in the pursuit of visionary goals is turning out to be one of the most costly.

—Walter Russell Meade

——Bottom Line——

[Crazy Years] *Considerable technical advance during this period, accompanied by a gradual deterioration of mores, orientation and social institutions, terminating in mass psychoses in the sixth decade...*

—Robert A. Heinlein, *Future History Timeline*

The priest quickly sliced into the captive's torso and removed his still-beating heart. That sacrifice, one among thousands performed in the sacred city of Tenochtitlan, would feed the gods and ensure the continued existence of the world.

—*Science* magazine, June 2018

Many of the classic science fiction writers depict civilizations which rise and fall, as real ones have done throughout history. Asimov's Foundation and Piper's Terro-Human histories are based on historical cycles at the scale of the fall of the Roman empire and the rise of modern western civilization. Heinlein's Future History has something of a finer focus. It's much easier to predict that a galactic empire will decline and fall at some imaginary date than it is to pick a decade that will be marked by cultural tumult—even only 20 years ahead. Heinlein's Future History chart was first published in 1941. It's not hard to predict a deterioration of mores. Virtually everybody, as they get older, sees that happening, because mores change and we all judge the new ones in terms of the ones we grew up with. Aristotle decried declining morals in the youth of his day—and Socrates had been executed for contributing to it. But in retrospect we can see that Heinlein's prediction still stands out. What's more, he predicted a hiatus in space travel after what he calls a "False Dawn." The Hiatus lasts for most of the twenty-first century, and is characterized by the "*New Crusade*," a religious dictatorship which suppresses scientific research and technological advancement. There is no doubt that the Green religion bears a great resemblance to Heinlein's New Crusade, although Heinlein gave it Christian overtones in his stories for verisimilitude in 1940s USA.

The Xhosa are a southeast African tribe whose economy and culture were traditionally based on cattle-herding. In the spring of 1856, Nongqawuse, a fifteen-year-old girl, a sort of Xhosan Joan of Arc, heard the voices of her ancestors telling her that the Xhosa must kill all their cattle and destroy their hoes, pots, and stores of grain. [\[125\]](#) Once that had been done, the very ground would burst forth with plenty, the dead would be resurrected, and the interloping Boers would be driven from their lands. Surprisingly enough, the beliefs found fertile ground among the Xhosa and spread like wildfire, within months receiving the imprimatur of the king.

The cattle were slaughtered. By the end of 1857 over 400,000 cattle had been killed. The Xhosa had refrained from planting for the 1856-57 growing season; there was no harvest. It is estimated that 40,000 Xhosans starved to death; that many again fled the country in search of food. By the end of 1858, three quarters of the Xhosa were gone.

The Xhosa meme plague is clearly something of a dramatic outlier in the history of religious fervor run amok. But it stands as a stark reminder that when social feedback, superstition, hopes and desires, and the suppression of doubt and skepticism (“faith”) line up, the resulting movement can make an entire people believe and do horribly self-destructive things, completely at odds with common sense, which would be clearly insane in an individual. In modern democratic societies, the outcome of a meme plague is more likely to be a flatline than a complete collapse. What you actually have is much more real and visible than what you might have had, so you will react more strongly when someone tries to take it away than when they merely close off future opportunities and growth.

If not particularly catastrophic on a broad social scale, insane meme patterns can be sustained for long periods. The Mexica (Aztecs) practiced regular human sacrifice for several centuries before it was put to a stop by the Spanish Conquistadors. Of course, feeding the gods and thus ensuring the continued existence of the world is surely a laudable goal. I suppose we have them to thank for the fact that the planet didn’t disappear in a puff of smoke before 1530.

My hypothesis for ascent up the Maslow scale is not by any means the only one that attempts to explain why culture took a hard left turn in the 60s and 70s (nor am I by any means the only writer espousing it). Turchin, for example, has a theory of dynamic cycles in history, not unlike those of

“Potiphar Breen” in Heinlein’s *Year of the Jackpot*. I don’t think the theories are necessarily incompatible: too many Stella Spaceleys might go right along with “elite over-production.” Nor are they incompatible with more classic theories of social evolution and development, such as Toynbee’s: we might well divide the elites into productive versus parasitic groups, of which the former would match his “creative minority.” A synthesis would make a fascinating study but would consume at least another entire book, probably many.

But the Maslow theory, broadly interpreted, explains the culture shift a bit more deeply than “they just got rich, and decided to enjoy themselves.” The LSD-soaked hippies of the counterculture *had* to find a different way to see things, or they would have had no self-respect at all.

Does it matter? Even more than the walls, you will find in every medieval European town a cathedral. These are gorgeous works of architectural art, which took in many cases literally centuries to build. The societies that built them were not rich; before the Industrial Revolution they barely made enough to feed themselves. We can quibble about how much we are or are not wasting on Green virtue signalling, but if they could build cathedrals, surely we can afford whatever expression of faith in the new religion we care to?

There are two reasons I think it matters in the long run. First, Green is not a “Big Gods” religion. The Big Gods hypothesis, so named in Ara Norenzayan’s book *Big Gods: How Religion Transformed Cooperation and Conflict*, is that societies of more than a certain size are enabled by a certain kind of religion. What makes the difference is belief in a god who is omniscient in a certain way, who in particular knows what’s in your own mind and is always watching you. A society in which everyone believes in a god who “knows if you’ve been bad or good, so be good for goodness sake!” is one in which people are more to be trusted, more likely to cooperate, more likely to trade instead of fight. Norenzayan backs up this hypothesis with an impressive array of experimental and historical research. In a civilization where belief in a Big God is effectively universal, there is a major advantage in the kind of things you can do collectively. In today’s America, you can’t be trusted to ride on an airliner with a nail file. How could you be trusted driving your own 1000-horsepower flying car? Before the collapse of “In God We Trust,” people didn’t even think about this. In

the 50s, to go on a hunting trip you simply walked on to the plane with your rifle and put it in the overhead rack.

The green religion, on the other hand, instead of enhancing people's innate conscience, tends to degrade it, in a phenomenon called "licensing." People who virtue-signal by buying organic products are more likely to cheat and steal than those who buy conventional—six times as likely in one classic experiment. [\[126\]](#) This turns out to be one of the more robust and reliably reproducible results in social science. [\[127\]](#)

In the 1970s SF movie *Short Circuit*, a military robot becomes conscious and intelligent due to a chance wiring error, and proceeds to become a likeable hero with many desirable character traits. At one point, the robot expresses a moral judgement, and the human protagonist asks, "Who told you that?" The robot replies, "I told me." In popular culture, the basis of morality had shifted from lifelong training by precept and example in the hard-won knowledge of your forefathers, to whatever feels right. The latter is far more susceptible to self-deception and virtue signalling.

The second reason it matters is the corrosive effect it has on science itself. Political funding of research has a strong tendency to bias scientists from a truth-centered view to an Eloi Agonistes one. Science is not the normal human way of thinking and operating; religion is. It has taken a 500-year battle, since Galileo, against the religious, authority-based, value-laden way of thinking to create a mental tool that gives us a chance to find actual, objective truth. But at the higher fervent-crusade levels of the Maslow hierarchy, the same kind of licensing subverts the honest, skeptical, value-free, single-minded search for truth that science requires. In one generation we have come perilously close to destroying objective science, an extremely rare treasure that has taken five centuries to build. Carl Sagan saw the same in his final book, *The Demon-Haunted World*:

Science is more than a body of knowledge; it is a way of thinking. I have a foreboding of an America in my children's or grandchildren's time — when the United States is a service and information economy; when nearly all the key manufacturing industries have slipped away to other countries; when awesome technological powers are in the hands of a very few, and no one representing the public interest can even grasp the issues; when the people have lost the ability to set their own

agendas or knowledgeably question those in authority; when, clutching our crystals and nervously consulting our horoscopes, our critical faculties in decline, unable to distinguish between what feels good and what's true, we slide, almost without noticing, back into superstition and darkness.

Whatever the proximate causes of the cultural shift in the 60s and 70s, the one incontrovertible fact is that it clearly did happen. By the Seventies, otherwise sane men were wearing polyester leisure suits with plaid pants and wide polka-dot ties. The culture of trust and "same boat spirit" have eroded significantly. This appears to have accelerated into the 21st century, but the latter-day consequences of cultural chaos are well outside our investigative purview, and in any event happened too late to contribute to the reason we don't have flying cars today.

What did contribute we can sum up fairly succinctly: susceptibility to baseless horror stories and hostility to technology, and particularly to energy. This formed the cultural substrate that supported the regulatory overreach which slammed the glass ceiling on the Henry Adams Curve and hobbles our new technologies in a quicksand of red tape. Like the Xhosa, we are destroying the very things that sustain us.

In later years I felt that there was a certain softening of moral fiber among the people, since the Hans had been finally destroyed with all their works; and Americans have developed a new luxury economy. I have seen signs of the reawakening of greed, of selfishness. The eternal cycle seems to be at work. I fear that slowly, though surely, private wealth is reappearing, codes of inflexibility are developing; they will be followed by corruption, degradation; and in the end some cataclysmic event will end this era and usher in a new one.

—Philip Francis Nowlan, *The Airlords of Han*

The United States stands at this time at the pinnacle of world power. It is a solemn moment for the American Democracy. For with primacy in power is also joined an awe-inspiring accountability to the future. If you look around you, you must feel not only the sense of duty done but

also you must feel anxiety lest you fall below the level of achievement. Opportunity is here now, clear and shining, for both our countries. To reject it or ignore it or fritter it away will bring upon us all the long reproaches of the aftertime.

—Winston Churchill (1946)

9 A Car in Every Garage

Universal aircars

Thanks to the perfection of air transport, everyone was free to go anywhere at a moment's notice. There was more room in the skies than there had been on the roads, and the twenty-first century had repeated, on a larger scale, the great American achievement of putting a nation on wheels. It had given wings to the world ... the ubiquitous little aircars had washed away the last barriers between the different tribes of mankind.

—Arthur C. Clarke, *Childhood's End*

The first occurrence to my knowledge of a description of universal aircars, ones generally available to everybody on the planet, is in E.E. “Doc” Smith’s *Skylark Three*:

The flier was a torpedo-shaped craft of some transparent, glassy material, completely enclosed except for one circular opening or doorway. From the midsection, which was about five feet in diameter and provided with heavily-cushioned seats capable of carrying four passengers in comfort, the hull tapered down smoothly to a needle point at each end. As Seaton entered and settled himself into the cushions, Rovol touched a lever. Instantly a transparent door slid across the opening, locking itself into position flush with the surface of the hull, and the flier darted into the air and away. For a few minutes there was silence, as Seaton studied the terrain beneath them. Fields or cities there were none; the land was covered with dense forests and vast meadows, with here and there great buildings surrounded by gracious, park-like areas. [\[128\]](#)

We are concerned here with prediction of universal ownership. Robur the Conqueror had been buzzing the skies of literary Earth since 1886. Personal-scale flying boats had been plying the tenuous atmosphere of

Mars, or rather Barsoom, since 1917; but they were the prerogatives of princes and the military, as were the actual aircraft of the day, and the ones in H. G. Wells' 1905 *War in the Air*. Somewhat closer to the mark, Tom Swift had been taking off in his own airplane from his front yard since 1910, but again he was depicted as the lone inventor, and not a representative of a general flying populace.

Smith's planet Norlamin, on which the scene above takes place, is in some sense an adaptation of the utopia depicted by H. G. Wells in *Men Like Gods* (1923). It is essentially a university planet, where everyone is interested in study and learning, mostly of science. Wells' conception is primarily political, and is part of his vision of "scientific socialism." In *The Shape of Things to Come*, Wells explicitly has the leader of the new world order point out that it "has an objection to private aeroplanes."

Oddly enough, *Things to Come* (the movie, with a script by Wells, based on the book) actually does have a flying car in it: the Norman Bel Geddes-style autogyro. Singular. There's only one, and it's reserved for the use of the political leader. The rest of the people in the utopian society shown as the culmination of the socialist reforms in the movie don't even have ground cars—they have to ride the monorails, or walk.

E. E. Smith, on the other hand, was trying to show what a world run by a wise, mature, and technically advanced race would look like. So while Norlamin was a nod to Wells' university planet, it came with a characteristically American point of view. On Norlamin, technology has freed everyone from any kind of drudgery, and put a relatively patrician lifestyle within everyone's grasp. Thus it was easier for Smith to imagine universal aircars, essentially by universalizing all the prerogatives of the well-to-do, in a day when the actual ownership of automobiles in the United States was still only about 20%.

The difference between the two visions has a definite European vs. American flavor to it. Wells' utopia is political first, and scientific second. The subtext is that society is richer and/or better off because scientific management has eliminated inefficiency, particularly war and economic competition. In Smith's story, the same concept is present—Norlamin is run by a wise council—but it's just background: the emphasis is on science and technology.

Another take on the universal aircar, but set on Earth—indeed, in New Jersey and New York City—was in this remarkable passage in John Campbell’s 1930 serial *The Black Star Passes*:[\[129\]](#)

Again Morey and Arcot were looking at the great Jersey aerodrome, out on the fields that had been broad marshes centuries before. Now they had been filled in, and stretched for miles, a great landing field, close to the great city across the river.

The men in the car above were watching the field, hanging inert, a point of glistening metal, high in the deep velvet of the purple sky, for fifteen miles of air separated them from the Transcontinental machine below. Now they saw through their field glasses that the great plane was lumbering slowly across the field, gaining momentum as it headed westward into the breeze. Then it seemed to be barely clearing the great skyscrapers that towered twenty-four hundred feet into the air, arching over four or five city blocks. From this height they were toys made of colored paper, soft colors glistening in the hot noon sunlight, and around and about them wove lines of flashing, moving helicopters, the individual lost in the mass of the million or so swiftly moving machines. Only the higher, steadily moving levels of traffic were visible to them.

“Just look at that traffic! Thousands and thousands coming back into the city after going home to lunch—and every day the number of helicopters is increasing! If it hadn’t been for your invention of this machine, conditions would soon be impossible. The airblast in the cities is unbearable now, and getting worse all the time. Many machines can’t get enough power to hold themselves up at the middle levels; there is a down current over one hundred miles an hour at the 400-foot level in downtown New York. It takes a racer to climb fast there!

“If it were not for gyroscopic stabilizers, they could never live in that huge airpocket. I have to drive in through there. I’m always afraid that somebody with an old worn-out bus will have stabilizer failure and will really smash things.” Morey was a skillful pilot, and realized, as few others did, the dangers of that downward airblast that the countless whirring blades maintained in a constant roar of air. The office

buildings now had double walls, with thick layers of sound absorbing materials, to stop the roar of the cyclonic blast that continued almost unabated twelve hours a day.

The commuter helicopters represent one of the first attempts to think about the effects of crowded skies—and not just from helicopters: note in passing the half-mile-high buildings.

The actual traffic to and from Manhattan from and to New Jersey over the course of an entire day is about a quarter million vehicles. [\[130\]](#) A small “commuter” helicopter of today, the Robinson R22, flies at about 110 mph [\[131\]](#) and could get out of the city in less than 5 minutes. If spread out over 12 hours, today’s traffic would put about 2000 copters in the air at any given moment.

By the way, the R22, which weighs 1370 pounds, has a rotor disc of 500 square feet and develops a downwash of about 35 mph. If you put half a million of them over Manhattan, their rotor discs would account for the entire area of the island; the text is not as exaggerated as it might sound.

Anticipation

The actual building of roads devoted to motor cars is not for the near future, in spite of many rumors to that effect.

—*Harpers Weekly* (1902)

Nothing has spread Socialistic feeling in this country more than the use of automobiles. To the countryman they are a picture of the arrogance of wealth with all its independence and carelessness.

—Woodrow Wilson (1906)

In 1902, H. G Wells penned a book, remarkably prophetic in many respects, that can be taken as the definitive *fin de siecle* take on the probable course of the 20th century, at least as far as technology is concerned. It was called *Anticipations of the Reaction of Mechanical and Scientific Progress Upon Human Life and Thought*.

Wells writes:

Railway travelling is at best a compromise. The quite conceivable ideal of locomotive convenience, so far as travellers are concerned, is surely a highly mobile conveyance capable of travelling easily and swiftly to any desired point, traversing, at a reasonably controlled pace, the ordinary roads and streets, and having access for higher rates of speed and long-distance travelling to specialized ways restricted to swift traffic, and possibly furnished with guide-rails. For the collection and delivery of all sorts of perishable goods also the same system is obviously altogether superior to the existing methods. Moreover, such a system would admit of that secular progress in engines and vehicles that the stereotyped conditions of the railway have almost completely arrested, because it would allow almost any new pattern to be put at once upon the ways without interference with the established traffic. Had such an ideal been kept in view from the first the traveller would now be able to get through his long-distance journeys at a pace of from

seventy miles or more an hour without changing, and without any of the trouble, waiting, expense, and delay that arises between the household or hotel and the actual rail. It was an ideal that must have been at least possible to an intelligent person fifty years ago, and, had it been resolutely pursued, the world, instead of fumbling from compromise to compromise as it always has done and as it will do very probably for many centuries yet, might have been provided to-day, not only with an infinitely more practicable method of communication, but with one capable of a steady and continual evolution from year to year. Let us consider ... in what direction are these new motor vehicles likely to develop? how will they react upon the railways? and where finally will they take us?

At present they seem to promise developments upon three distinct and definite lines.

There will, first of all, be the motor truck for heavy traffic. Already such trucks are in evidence distributing goods and parcels of various sorts. And sooner or later, no doubt, the numerous advantages of such an arrangement will lead to the organization of large carrier companies, using such motor trucks to carry goods in bulk or parcels on the high roads. Such companies will be in an exceptionally favourable position to organize storage and repair for the motors of the general public on profitable terms, and possibly to co-operate in various ways with the manufactures of special types of motor machines.

In the next place, and parallel with the motor truck, there will develop the hired or privately owned motor carriage. This, for all except the longest journeys, will add a fine sense of personal independence to all the small conveniences of first-class railway travel. It will be capable of a day's journey of three hundred miles or more, long before the developments to be presently foreshadowed arrive. One will change nothing—unless it is the driver—from stage to stage. One will be free to dine where one chooses, hurry when one chooses, travel asleep or awake, stop and pick flowers, turn over in bed of a morning and tell the carriage to wait—unless, which is highly probable, one sleeps aboard...

And thirdly there will be the motor omnibus, attacking or developing

out of the horse omnibus companies and the suburban lines. All this seems fairly safe prophesying.

Two things stand out from this exposition, seen from the perspective of a century later. The first is obvious: Wells' case for the private auto, as compared to the then dominant mode of travel, the railroad, is almost exactly the case to be made today for the private aircar versus airline travel. The second point is more subtle. He describes the car, as a piece of technology, quite foresightfully, and its use by the wealthy as adding independence to "all the small conveniences of first-class railway travel." It's a perquisite for the rich man on business or vacation; it has a driver, perhaps changed "from stage to stage." The common folk ride the motor omnibus, as they did the horse omnibus. Wells' notion of the social and economic penetration of automobiles in the twentieth century looks a lot more like the current status of private jets. The idea that everyman could have an automobile—having of course to drive it himself, with the concomitant implication that the roads would be filled with amateur drivers—is simply missing. This was a notion farther from the mind of the *fin de siècle* intellectual than time machines or invaders from Mars.

Wells wasn't the only one to miss the wave of cars that defined the twentieth century; on the contrary, he was probably the closest to getting it. The second-best-selling novel (after *Uncle Tom's Cabin*) published in America in the 19th Century was science fiction. It was Edward Bellamy's *Looking Backward*, a Utopian romance set in the year 2000. The plot is as follows: Julian West is mesmerized to sleep in 1887 and wakes up in the year 2000, when everything is wonderful. Occasionally he gets out and looks at some wonderful thing or another, but mostly he just sits and people lecture him about how wonderful things are. The reason things are wonderful is that the US has abolished money and private enterprise—essentially gone completely communist. People are not only much richer, but physically more well-formed and vigorous; greed and envy are unheard-of; people are more honest; they care more for each other; violence is unknown. Nations don't even make war on each other.

Bellamy was by no means opposed to technological progress. At one point in the book, the daughter of the house he wakes up in offers him music, and he assumes she will sing or play the piano for him. Instead, there is a

“music room” in the house where one can hear a live orchestra or organ recital via telephone. The telephone had been introduced 11 years before, and was one of the marvels of the age. But Bellamy’s grasp of, and imagination for, technology was negligible compared to Wells’. His notion of a century’s innovation in transportation (on the streets of Boston) is:

A heavy rainstorm came up during the day, and I had concluded that the condition of the streets would be such that my hosts would have to give up the idea of going out to dinner, although the dining-hall I had understood to be quite near. I was much surprised when at the dinner hour the ladies appeared prepared to go out, but without either rubbers or umbrellas.

The mystery was explained when we found ourselves on the street, for a continuous waterproof covering had been let down so as to inclose the sidewalk and turn it into a well lighted and perfectly dry corridor, which was filled with a stream of ladies and gentlemen dressed for dinner. At the corners the entire open space was similarly roofed in.

That’s right—awnings over the sidewalks so that people don’t have to carry individual umbrellas. More to the point, all of the innovations have to do with moving from a private mode of doing anything to a public mode. The family isn’t going out to a restaurant; they are going to the public, state-run, dining hall. All dressed for dinner, of course. A greater contrast to the burgeoning of informality, independence and individualism caused by the automobile in the 20th century can scarcely be imagined.

Needless to say, Bellamy missed the universal family car completely. In Bellamy’s defense, it seems likely that if he had accurately predicted the technology of the twentieth century, including not only cars for everybody but heavier-than-air flight, space travel, penicillin (Bellamy died at the age of 48 of tuberculosis), computers, and cell phones, his book would have been dismissed as a fever dream instead of becoming a popular phenomenon.

Historian of technology D. S. L. Cardwell writes: [\[132\]](#)

If we turn to contemporary speculation in order to gain some idea of men's expectations of the technology of their times, we find that in their predictions of the future, or rather their extrapolations of contemporary technological trends as they interpreted them, writers often made shrewd prophecies. Following the inventions of telegraphy and telephony, television could readily be imagined; air travel by heavier-than-air machines (usually powered by steam-engines and therefore boasting handsome funnels) was confidently predicted long before the Wright brothers' first flight. Even the atomic bomb was, it is claimed, forecast by H. G. Wells not very long after the beginnings of sub-atomic physics.

It is, however, a truly remarkable fact that on the very brink of an economic-technological revolution unparalleled in history no one foresaw the *universal* motor car and all that it was soon to imply. This failure on the part of informed and perceptive men to grasp the significance of what was going on under their very noses must make us suspicious of all attempts to forecast technological developments even one or two years ahead, much less ten or twenty.

Was there something technological that they missed? Yes: productivity. If it takes ten workers a year to build a car, your economy is simply incapable of building enough cars for everybody to have one, and a car will have to cost at least ten years of the average worker's wage. Of course, labor is only one of the factors of production; you have to count the cost of the others, as well: materials, buildings, transportation, production machinery, and so forth. As a rule of thumb over the twentieth century the other factors together cost about as much as the labor. In the 19-Aughts, the average worker produced about 5 cars per year; by the Twenties, he produced 20. It was that factor-of-four productivity jump, spearheaded by Henry Ford and the assembly line, that made the family car possible. [\[133\]](#) That was the technological advance the prophets missed.

This illuminates our investigation of flying cars, and other promised future technology, considerably. As Wells prophesied, the world did indeed fumble along from compromise to compromise as it always has done and as it will do very probably for many centuries yet. No wise global government of

enlightened airmen took over and ushered in the era of technological nirvana. And yet, all the pundits to the contrary notwithstanding, we did get the family car. It seems all too likely that if the pundits had actually been in charge, that Failure of Nerve would have become an enforced reality instead of an obscure missed prediction. We would have sidewalk awnings, no cars, and the Great Stagnation would have started in 1910.

Mind the Gap

Hans Rosling was a world health economist and an indefatigable campaigner for a deeper understanding of the world's state of development. He is famous for his TED talks and the Gapminder web site. He classifies the wealthiness of the world's population into four levels:

1. Barefoot. Unable even to afford shoes, they must walk everywhere they go. Income \$1 per day. One billion people are at Level 1.
2. Bicycle (and shoes). The \$4 per day they make doesn't sound like much to you and me but it is a huge step up from Level 1. There are three billion people at level 2.
3. The two billion people at Level 3 make \$16 a day; a motorbike is within their reach.
4. At \$64 per day, the one billion people at Level 4 own a car.

(Numbers are rounded for simplicity.) There are of course parallel improvements along other axes as well, including Rosling's famous washing machine, standard of housing, diet, and infant mortality rates. But we can use transportation as an example, given our overall subject.

The miracle of the Industrial Revolution is now easily stated: In 1800, 85% of the world's population was at Level 1. Today, only 9% is. Over the past half century, the bulk of humanity moved up out of Level 1 to erase the rich-poor gap and make the world wealth distribution roughly bell-shaped. The average American moved from Level 2 in 1800, to level 3 in 1900, to Level 4 in 2000.

We can state the Great Stagnation story nearly as simply: There is no level 5. Another factor of 4 would put Level 5 at about \$100K/year (per household), which characterizes about a quarter of the US population now. And yet we still only drive cars. The basic capabilities of personal transportation have seen no such quantum jump as we saw with the previous levels.

An easy way to see what is happening is to note that the countries still at Levels 1-3 on the development curve have *not* seen a flatline in their

energy-use per capita over the past 50 years, but on the contrary have continued increasing (or in many cases, started increasing) on a Henry Adams-like curve just as we did before 1970.

——Bottom Line——

My Lords, these railroads will enable the working classes to move about!

—Duke of Wellington (1830)

Yes. An excellent ambition. But our new order has an objection to private aeroplanes.

—H. G. Wells, *Things to Come*

Throughout history, poverty is the normal condition of man. Advances which permit this norm to be exceeded—here and there, now and then—are the work of an extremely small minority, frequently despised, often condemned, and almost always opposed by all right-thinking people. Whenever this tiny minority is kept from creating, or (as sometimes happens) is driven out of a society, the people then slip back into abject poverty.

This is known as “bad luck.”

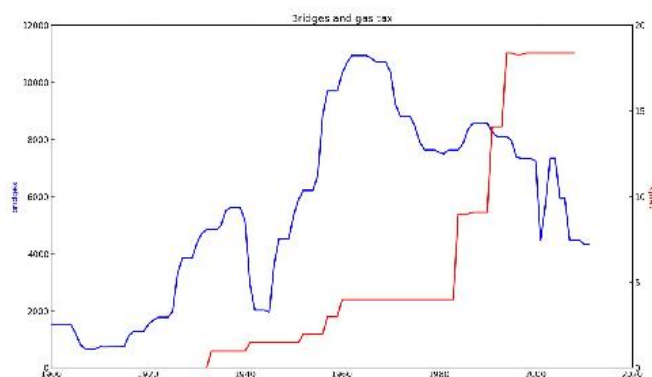
—Robert A. Heinlein

The new world order has not only an objection to private aircraft; it has an objection to private cars as well. The pantookas and wozzles that the grinchies of fashionable ergophobia have hated the most and tried to take away the longest and hardest have been our cars.

It seems virtually certain that if we had had the cultural and regulatory environment of the Great Stagnation from, say, 1910, the development of universal private automobiles would have been suppressed. Heinlein’s “bad luck” has overtaken us and we are back to the *status quo ante* where the most insightful pundits quite reasonably couldn’t foresee them.

Among the technologies that made a big difference in the Twentieth century were the technologies of personal transportation. The automobile itself, and then the highway system, enabled the rise of the suburbs. There’s plenty of

cheap land out there, 25,000 times cheaper than land in Manhattan, and up until the Stagnation people were making more and more use of it. The trend has stopped, if not reversed. The national investment in transportation infrastructure peaked in the Sixties:



Bridges built in the US, [\[134\]](#) and federal gasoline excise tax rate per gallon. [\[135\]](#)

By 1970, the nascent Green religion had gotten enough traction that cars began to be demonized. Cars were buried as part of the original Earth Day celebrations. Regulators swarmed like locusts. In 1974, cars were required to have an ignition interlock that prevented them from starting unless the seatbelts were fastened. (The national 55-mph speed limit was also a 1974 innovation.) This was a good measure of how different (and how anti-car) the opinions of the Eloi Agonistes were from the average American; the interlocks (and 85-mph speedometers) were so unpopular that Congress quietly repealed them over the heads of the regulators. Even so, by the end of the 70s there was virtually nothing about a car that was not dictated by regulation. Cars all look like half-digested sneakers today for a reason. (See Appendix C) It's clear that if we had had the same planners and regulators in 1910 that we have now, we would never have gotten the family car at all. A recent study by the London School of Economics [\[136\]](#) strikes a note that brings the suppression of flying cars into well-defined juxtaposition with the Great Stagnation:

In the 20th century, tumbling transport costs weakened the gravitational pull of the city; in the 21st, the digital revolution has

restored it. Knowledge-intensive industries such as technology and finance thrive on the clustering of workers who share ideas and expertise. The economies and populations of metropolises like London, New York and San Francisco have rebounded as a result.

They somehow missed the fact that *transport costs quit tumbling*. I doubt there is a more comprehensive nutshell for the Great Strangulation. A major component of the opportunity cost of travel is the time taken. As the highways became more congested, time cost rose; traffic congestion today is five times worse than it was 25 years ago. [\[137\]](#) But planners have increasingly adopted a car-hostile ideology, and are designing cities intentionally to make driving more costly and difficult.

Over the course of the Great Strangulation, the enemies of the car have gotten a lock on the urban planning industry and the coalition of special interest groups it mutually enables. [\[138\]](#) The federal gasoline excise tax rate rose from 4 cents per gallon (since 1959) to 18 in 1993. Instead of building more highways and bridges, it goes more and more to worthless, expensive public transport and metrorail projects. Public transit accounts for between 2 and 3 percent of the passenger miles of urban travel, but gets between 20 and 30 percent of transportation expenditures at all levels of government. [\[139\]](#) Transit passenger miles outside of urban settings are negligible.

Light rail is a darling of car-hating academics and bureaucrats, but it is a disaster in time cost of travel (see Chapter 11). First, there is a built-in tradeoff involving the number of stops: the more stops, the closer to your actual start and destination they are likely to be, but the more times the train will stop on the way, lowering average speed. The public transit in San Francisco has been measured as providing an average of 8 mph to its riders. [\[140\]](#) This puts public transit riders at about Rosling's Level 2; your average speed on a bicycle is 9 mph. A sample survey using Google Maps indicates that transit typically takes something like three times as long as a car would. My personal experience, which includes both driving and taking transit in many major American cities and several European ones, tends to confirm this. It includes a high average latency and a "three vehicles problem."

As the Duke and Mr. Wells point out, this isn't something particularly new. Travel at will was a prerogative of the aristocracy or the new political elite. The question, among others, that we started out to ask was why we don't have flying cars by now. The obvious answers, such as that they were technologically infeasible, or even that they would be too expensive, turned out not to be right. Instead, perhaps the really fascinating question turns out to be why we ever got the family car in the first place. The pundits of yesteryear couldn't see it coming. Their opposite numbers today disparage and despise it, and have done everything in their power to cripple it. But in spite of them all, something wonderful happened during the first half of the Twentieth Century.

Technologically, the answer is that the Industrial Revolution ran longer and stronger than people had realized possible, and increasing productivity made the car affordable to the masses. Socially and politically is a harder question.

It is made harder yet by the fact that it was not merely a reversal: the proximate cause of the Great Strangulation, excessive regulation and liability, was not something that got removed for us to have personal automobiles in the first place. In fact, the rise of the family car largely coincides with the first regulation explosion of the Progressive Era. Perhaps the best way to see what happened is to go back to the situation just before the rise of the car in the early 20th century. This was of course the Wild West period, the days of the winning of the frontier. The value of powered personal vehicles, ranging from cars to trucks to tractors, was as obvious as it was crucial. But I think something more subtle was just as formative.

As we have seen, both phenomena are part of a dynamic trajectory. The self-reliant culture of the frontier remained strong in America in the early 1900s; along with the huge increase in productivity of the Industrial Revolution, it made universal private cars possible. At the same time, it was on the decline, due not only to the closing of the frontier but due to the car itself.

As with many technologies, cars seem to have opposite effects when seen on different scales. Up close, a car is a tool of personal autonomy. In the large, it increases social interaction as the person with a car has a choice among 100 times more people to interact with. A substantial growth of an

inter-dependent manufacturing and support industry, as well as the increase in the ability of people with cars to interact with each other, were both countervailing forces to the self-reliant frontier culture.

Remember the story of the Eloi Agonistes and self-deception. Remember that Trivers, and his latter-day disciples Simler and Hanson, tell us that self-deception is primarily a mechanism to assist deceiving others, promoting one's apparent status in their presence. After a long period of sustained social interaction, many forms of self-deception will become baked into the culture, and major social institutions will become in large part vehicles for virtue signalling.

But on the frontier, where a majority of one's efforts are not in competition with others but directly against nature, self-deception is considerably less valuable. A culture with a substantial frontier is one with at least a countervailing force against the cancerous overgrowth of largely virtue-signalling, cost-diseased institutions. We had such a culture at the beginning of the 20th century. It was probably a significant factor in the rise of the motorcar.

Could it happen again?

Part II. Profiles of the Present

10 Ceiling and Visibility Unlimited



The classic DC3

For once you have tasted flight you will walk the earth with your eyes turned skywards, for there you have been and there you will long to return.

—Leonardo da Vinci

You can always tell when a man has lost his soul to flying. The poor bastard is hopelessly committed to stopping whatever he is doing long enough to look up and make sure the aircraft purring overhead continues on course and does not suddenly fall out of the sky. It is also his bound duty to watch every aircraft within view take off and land.

—Ernest K. Gann, *Fate is the Hunter*

Virtually every time I bring up the subject of flying cars to an acquaintance, I get much the same reaction. After an initial giggle and reference to the Jetsons, people opine that they could never become the common mode of travel because the average person who drives a car couldn't fly a plane. If everybody had one, there would be crashes galore.

A proper answer to this objection should be based on a substantive understanding of just how hard it really is to fly a plane. Given that, one could reasonably guess how much easier it would be with various proposed mechanical or cybernetic aids, or estimate how many people might actually

be able to do it safely. In general such an understanding allows the futurist to have a common-sense basis for prediction and provides a sanity check. Given 40 years of experience in computers ranging from processor design to robotics (not to mention a PhD in the subject), I have always felt that I had a common-sense basis as a futurist in the areas where developments were driven by digital technology. But I had no real experience of flying. I could do the math as well as the next person, but I lacked any seat-of-the-pants foundation for any pronouncements about flying machines.

Thus as part of the research for this book, I determined to become a pilot (and incidentally acquire an airplane). The project, though somewhat lengthy, has been enormously rewarding. In particular, I feel I understand a lot more about what a flying car would actually be like.

Throughout the rest of the book, I have tended to analyse air travel as if it were purely a question of time, or economic productivity, or the like. It is much easier to measure such things, but they don't come close to capturing the full value of flight. Flying has been a dream of mankind since time immemorial, and with good reason. This world is a wonderful place, and you simply don't see it from the ground. Your point of view is terribly limited crawling around on the surface. People get the same experience of taking off blinders and seeing the whole world from mountain climbing, or even from dining in a top-floor skyscraper restaurant. But when you fly, you get to take the mountain with you.

There is an interesting phenomenon in psychology related to futurism (and to some extent science fiction) called construal level theory. The way we imagine things ranges over a spectrum from "near mode," in which things are close, with bright colors and loud noises, complex, and basically "in your face." In "far mode," things are muted, blue, simpler, more abstract. Futurism must by its nature see the world in far mode. The thing that struck me about flying is just how much the world seen from an airplane is literally in far mode: you can't hear anything at all outside your own airplane; colors are muted and bluer seen through miles of air and haze; details disappear and only larger outlines remain, outlines you can't see at all from the ground. You see the world more abstractly—but you see a lot more of it.

The World of ... Yesterday

The prisoners, without memory of the past, had nothing upon which to base a speculation of the future.

—Robert Sheckley, *The Status Civilization*

The very first thing you notice when you walk out on to the apron at a small general aviation (“GA”) airport is the feeling that you have been transported to Cuba, where most of the cars are much-maintained models from the Fifties. The same is true of GA aircraft in the US today. The plane I ultimately bought, a 1977 Beechcraft, is about average. When did you last ride in a 1977 automobile?

The experience of having fallen through a time warp continues when you get into the airplane. You might have the very latest electronic noise-cancelling aviation headset, but you plug it into the radio with 2 old-fashioned quarter-inch phono plugs (they are actually slightly different sizes so they have to go in the right sockets). Your instrument panel is covered with round mechanical “steam gauges.” The basic types of these instruments were set by the RAF during World War II over 70 years ago. Your engine has a carburetor and a choke, and burns leaded gasoline. Once you start learning how to do navigation computations, you’ll find that you are expected to use ... a slide rule. [\[141\]](#)



Furthermore, the units of measure in aviation are a dog's breakfast. Speeds are measured in knots (nautical miles per hour), but visibilities are measured in statute miles. Altitudes are in feet, sometimes measured above sea level ("MSL") and sometimes above the actual ground ("AGL"). Your altimeter reads MSL but the tower reports cloud heights in AGL. Except when they are flight levels, which are the number of hundreds of feet above an imaginary surface that is where sea level would be according to an altimeter set to a barometer reading of 29.92 inches of mercury. Climb rates are measured in hundreds of feet per minute. Runway lengths are also in hundreds of feet. Temperature and dew point are Celsius; dates and times are as of Greenwich, England. Course bearings are measured in degrees, but not from true north; they are measured from magnetic north, which varies depending on where you are. See the slanted dashed lines on the chart. Wind directions you see written down (e.g. the airport weather report on the internet) are true; ones you hear on the radio are magnetic. Bearings reported to you by ATC to watch for other traffic are in "o'clock" from your present course.

Beside the carefully-kept-up fleet of planes that would grace any antique car show, you will also find at your friendly neighborhood GA airport a remarkable number of homemade airplanes. In any given year, more homebuilts are put into service than factory-built small private aircraft. One of the more ironic regulatory pathologies that has shaped the world of general aviation is that most of the planes we fly are either 40 years old or homemade—and that we were forced into that position in the name of safety.

Without the Great Strangulation, going by the trend line up to about 1980, the industry should be shipping on the order of 50,000 planes a year, total planes in the air would be over a million—and they would be, on the average, a lot newer than the ones flying now. And, as I'm sure your experience with automobiles will bear out, a lot less likely to break down. In World War II, in less than 4 years 1941-5, the Army Air Forces lost about 15,000 airmen and 14,000 aircraft in 53,000 total aircraft accidents—*inside* the continental US. 1000 planes simply disappeared flying across the oceans to theaters of operation. Once they got to combat, 23,000 were shot down and another 21,000 were lost to accidents, weather, and so forth. There were 122,000 airmen casualties total. [\[142\]](#) It is quite reasonable to

say that the wartime way of thinking—get the job done whatever the cost—served to obscure the very real dangerousness of flying (especially since they sent fliers out with as little as one hour of training in the aircraft they were flying). It is quite likely that this contributed to a false sense of what risks we would accept in the peacetime post-war world as compared with the benefits of flying.

So how dangerous is general aviation, when all is said and done? The FAA and pilots associations make a big deal of flying safe, and thus paradoxically spend a lot of time talking about hazards and dangers and accidents, resulting in an anecdotal impression of a dangerous undertaking. The people who actually know would be my insurance company. The price for my all-hazards airplane insurance, covering everything from hitting a sparrow on approach to crashing into someone's house, is less than \$800 per year, in other words comparable to car or home insurance and considerably less than medical.

The leading cause of death among active pilots is ... motorcycle accidents.

Take-off

Note: You can buy a used airplane for about the same price as a new sports car.

Riddle: What's the main difference between the sports car and the airplane?

Answer: If you speed up the sports car to about 75 miles per hour and pull back on the steering wheel, nothing very interesting happens.

—John Denker, *See How It Flies*

Perhaps the most amazing thing about an airplane is that it was possible to build them with the technology of a 1903. A working airplane can be an incredibly simple machine: a structure with a certain shape, which acts as a glider, and a motor attached to an oddly-whittled piece of wood which forms the propeller. There need be no transmission between engine and propeller (my plane has none); the only controls that are absolutely necessary can be built by tying wires from a single stick to hinged extensions of the wings and tail. Many ultralight hobby aircraft are built in exactly this way.

So a basic usable airplane can be mechanically simpler than a basic usable car. We don't see very many people driving around in cars they built in their garages (although yes, there are a few).

On the other hand, the plane is definitely harder to drive. We are evolved to navigate in two dimensions, not three. Our instincts need some help with going up and down, being tilted sideways, and so forth. We are absolutely flat-out terrible at flying when we lose visual contact with the ground: you literally cannot tell which way is up. In fact it was solving the problem of control, attitude and steering, that was the Wright brothers' seminal contribution to flying. They made bicycles, after all, and understood the importance of balance, and how it tied in with steering.

Back on the first hand again, flying is absolutely a learnable skill. In my experience, it's roughly on a par with riding a bicycle, with the hardest part, landing, being about like skiing. That is, the actual physical control of the

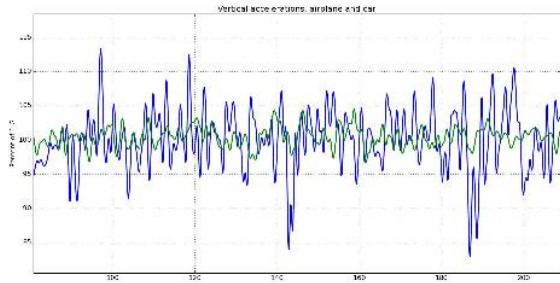
airplane is like that. In real life, the pilot is doing four jobs at once: engineer for the motor and other mechanical systems of the plane; aviating it as just described; navigator; and radio operator. Each one of these alone is not a really hard job, but doing all four at once is a little like delivering a really good serve in tennis or bartending at a busy bar. It takes enough practice so that much of what you're doing is habit and second nature so you don't get overwhelmed.

As we pointed out in Chapter 2, the main thing different between a plane and a car is the danger of going slow, particularly when you are low and trying to land. You have to be able to give full attention *right now* to everything the machine is doing and keep it doing what it is supposed to. The one effect I noticed after getting a pilot's license on any other activity I did was that I became much better at parallel parking.

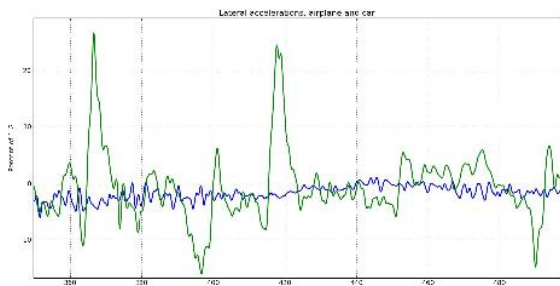
There are plenty of people I wouldn't like to see flying planes. I would have to guess that perhaps half the people who currently drive cars shouldn't fly planes under manual control. But the bottom line has shifted since 1962.

There are many more possibilities: a more-or-less continuous spectrum between full personal control, to FADEC (engine control) systems which relieve you of some of the engineer's duties, to GPSs which make navigation much much easier, to autopilots. There are now fully autonomous aircraft which can do the entire job by themselves; you need only tell them where to go.

Perhaps the most unexpected aspect of having an airplane has been how many of my friends and acquaintances would turn down offered joyrides. The number isn't huge, perhaps 25%, but there are plenty of people out there who get queasy from the ride in a small plane. I took an accelerometer for a ride in a car on town and county roads, and on a plane ride on a blustery day at a fairly low cruising altitude to get a handle on the difference. (Note that flying a mile up on a calm day is smoother than driving on the highway.)



The plane (blue) bounces you up and down more than the car (green) does on a blustery day. Horizontal scale is just seconds into the trip.



But surprisingly, the acceleration, turning, and particularly braking in a car (still green) are much stronger than the sideways forces you experience in a plane. Note the different scale.

It turns out that the accelerations you experience, even on a bumpy blustery day, in the airplane are not greater than you get in a car; they are just different. In particular the bumps you get are vertical, and of slightly higher frequency. In a car you are subject to forces just as great, indeed greater, but typically they are sideways—starting, stopping, and turning. It seems likely that if we grew up riding in airplanes, it is something we would get used to. A vast majority of people are able to handle the experience of riding in a large commercial jet. The susceptibility of an aircraft to being tossed around turns out to be fairly strongly (inversely) correlated with its wing loading, that is, the ratio of the plane's weight to the surface area of its wings. This is a problem that is susceptible of a technological solution, and we shall consider it below.

The other problem people have with small planes, not to mention large jets, is noise. Inside your plane you typically wear a noise-canceling headset.

Outside, the plane can be heard a mile away, particularly on takeoff when the throttle is revved up full. This is another problem that can be addressed technologically; but it is, perhaps surprisingly, the hardest of the technological problems.

Need a Lift?

It is blowing gale-force winds outside, 35 knots sustained with gusts in the 40s. The Bay is completely covered with whitecaps. The house is being pelted by pine cones blowing off the trees; occasionally a branch comes down. Some houses lose siding or shingles. You can walk upright in a gale but you must pay careful attention to each step. You have to lean hard against a door to open it into the wind.

Now imagine you are in a hurricane-force wind, twice as fast at 70 knots. The forces you feel are not twice those of the gale; they are four times as much. You cannot stand upright; the wind force is similar to your weight. We are accustomed to traveling at 70 knots, but we rarely experience it directly, and typically are unaware of how much force is being exerted by the air. At a nice flying-car speed of say 350 knots, forces are 100 times that of the gale. The trick is to use them to hold us up in the air, without being blown back to a standstill.

Imagine a box, one foot cubed in size. At sea level, the ambient air presses on each side of with a pressure of 14.7 pounds per square inch, or a little over a ton on each side. The box just sits there, however, since the forces balance for a net of zero. [\[143\]](#) Now imagine the box contains vacuum, and that the top of the box magically vanishes.

For a millisecond or so, two things will happen:

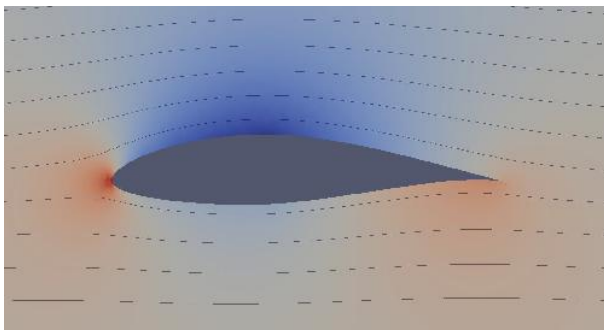
- The upward force on the bottom of the box will not be balanced by a force on the top.
- Air above the box will accelerate downward.

Basically this is how a wing works. The difference is that the air is rushing sideways past the wing, so that when the accelerated air in our *gedankenexperiment* would have hit the bottom of the box, the air passing over the wing falls behind it and continues downward. There's a conceptual

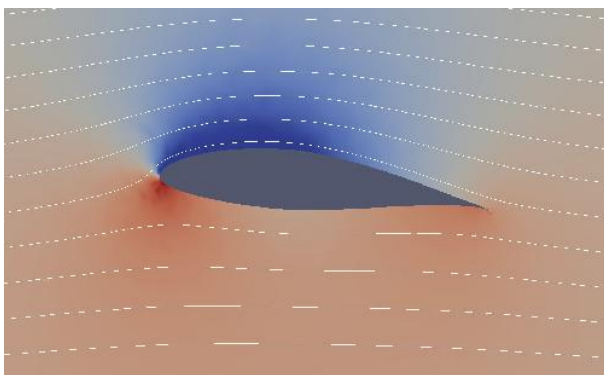
similarity to the reason a satellite stays up: it falls the same as any other object in the Earth's gravitational field, but it has such a sideways velocity that the surface curves away from it at the same rate it falls. Intuitively, we say that there is a centrifugal force holding the satellite up; we could as readily say that the centrifugal force of the curved path of the air over a wing produces a pressure gradient that maintains a partial vacuum there.

[\[144\]](#)

Typical airplane wings derive most of their lift from this lowering of pressure above them, rather than from raising it below them. This by no means necessary; in fact when the flaps are lowered on a conventional wing, a rise in pressure below is a major part of the lift enhancement. The reason for the usual design is efficiency; such a wing can have a higher lift-to-drag ratio and thus require less thrust for a given amount of lift.



A NACA 64(3)-618 wing section at 0 degrees angle of attack, with the flow of the air around it. [\[145\]](#) There is an area of high pressure (red) underneath, and a larger region of low pressure (blue) above it. A wing like this can have a theoretical lift-to-drag ratio of over 100. [\[146\]](#)



The same wing at an angle of attack of 6 degrees. Notice that the high-pressure area where the oncoming wind strikes the leading edge (the “stagnation point”) has shifted around to the bottom, and the low-pressure area is deeper, broader, and shifted to the front. Lift coefficient rises from 0.4 to 1.0, meaning you get two and a half times the lift.

The hardest thing to grasp intuitively about any (subsonic) fluid flow pattern is that the pressure changes affect all of the air in all directions—so the incoming air seems to “know” ahead of time that the wing is coming and rises to meet it (the upgoing front of the circulation pattern). What’s happening, of course, is that with a high pressure area under the wing and a low pressure one over it, there is a pressure gradient pushing the oncoming air up. If you zoom back out from either of these close-up views of the wing and flow, the “farfield” flow is exactly level, left to right. The lift force is at right angles to this flow, i.e. it is a force exerted straight up. In theory or a wind tunnel, the drag force can be as low as 1% of the lift. Thus if the path of the wing through the air is tilted even slightly downward, the lift vector is tilted forward enough to overcome the drag; that’s how a glider (or autogyro) works. A well-designed glider can go 50 feet forward for each 1-foot drop in altitude.

Lift is proportional to the square of the speed and, within certain limits, to the angle of attack—how tilted the wing is with respect to the incoming airflow (“relative wind”). The thing that makes piloting an art and a skill is that the angle of attack relationship fails at an angle somewhere between 15 and 20 degrees. Instead of increasing lift, further tilt causes it to disappear, a phenomenon known as stall.

The word “stall” was used in 1904 by Wilbur Wright in describing the phenomenon, and it stuck. When the Wright brothers first made wings, they modeled the shape on birds’ wings—thin, with a concave undersurface. These can have high lift, but they must be oriented very precisely to the oncoming air. The bird does this as automatically as you balance on your feet, but for a rigid wing, rigidly attached to a machine, that design was finicky: piloting a Wright airplane required a lot of skill and constant attention. Aviation pioneers through the Teens modified the wing sections to

have more rounded leading edges and flatter bottoms. These are considerably easier to fly.

If you slow your airplane down, reducing the velocity factor of lift, you must pitch the nose up, increasing the lift coefficient factor, to maintain lift equal to the weight of your plane. As you do this, you will begin to notice a buffeting and deep vibration, as if you were driving on a very bumpy road. The speed of the air past the wing is no longer enough to get it past the low pressure area, which pulls it back in. No longer in “orbit,” it begins hitting the back of the wing. Vortices, i.e. “bubbles” of rotating air, form over the trailing edge of the wing. As a vortex forms, it ruins the effective shape of the wing, as far as the airflow around it is concerned, and cuts down the lift. Then the vortex blows off, lift is momentarily restored, and you’ve felt a bump. This happens several times per second. Your wing is beginning to stall. If you pitch up any more, the flow will not be able to reattach even momentarily, and you will lose lift dramatically.

Stall, above all else, is what makes flying difficult and dangerous. The handbook of your airplane will list a “stall speed”, but that is at best shorthand. A wing can stall at any speed; it stalls at a particular angle of attack. The stall speed listed is the speed at which the stall angle of attack generates lift equal to the weight of the airplane. Go slower than that speed, and either the plane stalls, or it isn’t generating lift equal to its weight. In either case, it goes down.

As my flight instructor told me: “To go up, pull back on the yoke [which increases your angle of attack]. To go down fast, pull back some more.”

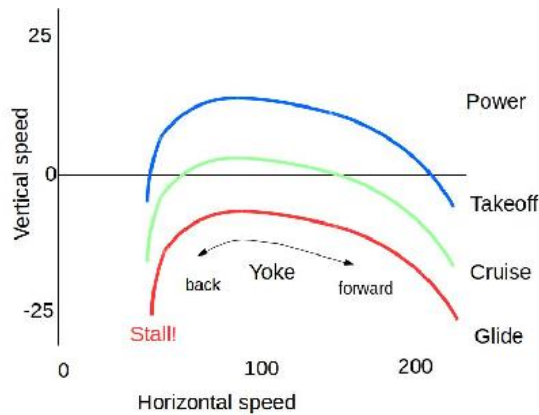
Similarly, being low is dangerous, too. If you’re high, you can afford to fall several hundred feet while untilting the plane, speeding up, and regaining normal flight configuration. But you can easily fall the height of a 20-story building while doing this. So going low and slow is a particularly dangerous combination. It’s no wonder that airplane accidents cluster around takeoff and landing.

It’s quite counterintuitive, given our experience in cars, that going slow is dangerous. If I had to list any one thing that was the biggest problem with having every Tom, Dick, and Harry flying airplanes, this would be it.

Zimmerman, La Cierva, and Pitcairn were right.

The way an airplane reacts to its major controls is counterintuitive, but it can be summed up neatly in a diagram that turns the power curve upside

down. Use vertical speed instead of horsepower for the vertical scale; each 100 HP can raise a 3300-pound airplane at 10 knots (although your vertical speed dial will call it 10 hundreds of feet per minute).



The power curve, speed form. Both scales are speeds. Pushing or pulling the yoke (which tilts the nose down or up respectively) moves you along the curve; pushing or pulling the throttle moves the whole curve up or down.

On the front end of the curve, you push the nose down and go faster, both forward and downward: you're diving, and cashing in your altitude energy as speed. In the middle is a speed that is the best climbing speed with the engine on, and the best gliding speed with it off. At speeds less than this, on the back end of the curve, things work backwards: pulling the nose up makes you slow down and go down, and you're flirting with a stall.

The curve itself shifts up and down as you add or remove engine/propeller power. On a particular airplane, the shape of the curve may change slightly, but that's a secondary effect you can usually ignore. For example, the peak of the curve is the best climb speed with full power and the best glide speed with no power. These are typically listed separately for a given airplane but will generally be within a few knots of each other.

One of the less obvious or intuitive things about flying is that you typically move the yoke, pointing you up or down, to go faster or slower, while actually going up or down with the throttle. This makes more sense if you look at the intersection of the "cruise" curve and the zero-vertical-speed line. To go up, move the whole curve up, with the throttle. To go faster,

move along the curve with the yoke, only adjusting the throttle to maintain altitude.

Birds

The only times I have ever considered myself on the edge of serious danger while flying have been when birds—particularly big ones, such as eagles and vultures—flew right into my path on takeoff or final approach. These are, of course, the times when you are low and slow, and have the least margin to maneuver without losing control. There has been a lot of publicity recently about drones and how they might interfere with aircraft, but in my experience birds are a bigger problem by orders of magnitude. I've seen a total of three drones in the air in all my flying; I see more than three birds every single time I go up. I've even encountered an eagle at 3000 feet, well above where birds usually fly; we both stared at each other as if to say, "And just what do you think you're doing up here?"

Weight and Balance

The other aspect of an airplane that is significantly different from a car is that the airplane is essentially balanced on its wings. The elevator gives you control in pitch, but it is like the toe you keep in contact with the desk when you lean back and balance on the back two legs of your chair. It will not support you if you are seriously unbalanced. So loading passengers and cargo into the plane is like loading a rowboat: you have to pay attention to where the center of gravity is, and in particular to the total weight. If the gunwales are awash, don't lean out over the side! The closer to the max load you are, the more nearly you must be perfectly balanced.

Aerodynamic forces on an airplane vary with the square of the speed through the air. If you increase the weight, you can increase the speed to make up for it. You glide at the same angle, for example approaching for a landing, but you move along the same path faster. Which means that that runway with plenty of room when you were flying by yourself suddenly looks a lot shorter when you have some passengers and luggage on board.

The Winds of Gath

KMFV 141515Z AUTO 31021G30KT 10SM CLR 04/M08 A3012
RMK AO2

—KMFV (Accomack County, VA airport) AWOS

Sorry! We only have crosswinds here.

—Barbara Haxter, manager, KMFV

Perhaps the next thing you notice upon getting into aviation is how much more aware of the weather you become. A simple example will help us get started. The METAR quoted above is the weather report automatically generated at the local airport. It generally indicates a fine day: visibility is 10 statute miles, and the sky is clear. In fact it is a beautiful sunny day outside. There is just one catch, revealed in the report: there are strong winds, 21 knots gusting to 30, and in a direction that happens to blow directly sideways across the one runway here. And that's why I'm sitting inside writing instead of out flying.

Many of the new skyscrapers built in the Sixties in New York (and other cities) had heliports on their roofs. It was an almost universal assumption in the science fiction of the period that you took the elevator up to catch a taxi. It seemed that the technology to make this a reality was present, at least in first-generation form. But even big, turbine-powered helicopters are susceptible to wind, especially gusty wind. Rooftop heliports proved too dangerous, even with highly trained, professional pilots.

With today's technology, much less that of the Sixties, building a capable, efficient flying machine requires that the design be optimized for flying. Virtually all airplanes are so optimized; they are ungainly and slow on the ground. They require wide taxiways with relatively gentle turns. They are dangerous to be around; besides the unencased propeller, the air blast will take any loose pebble on the pavement and throw it backward as hard as you could have thrown it by hand. They can't back up under their own power; to back into a parking space or hangar the pilot has to stop the engine, hop out, and push the plane by hand (or by tractor if it's too heavy).

That's one of the reasons for ground controllers at busy airports: most taxiways are one-way-at-a-time and the traffic needs direction from someone in a tower who can see everything at once. The tower is actually more for seeing ground traffic than air traffic. Air traffic controllers look at radar screens.

Needless to say, a machine optimized for flying is particularly vulnerable when switching from air to ground mode, i.e. landing. The airplane wants to point in the direction it's moving through the air, and when it touches ground, it wants to roll the direction it's pointing. If the air itself is moving sideways, the plane will too, and it's trying to touch down at highway speeds.

When I was just beginning to be aware of the issue of wind, I was particularly disturbed that our local airport seemed to have been sited at the windiest point in the whole county. It always seemed to have winds about ten knots higher than any other weather station in the area. After a while, though, I came to realize that the winds at the airport were roughly the same as those at a thousand, or even five hundred, feet altitude. The other weather stations are sheltered by the many stands of one-hundred-foot trees we have. The airport is a big, long, clearing. And that's a good thing.

Imagine that you're flying along at 1000 feet, approaching the airport for a landing. You're flying into the wind, which is blowing at 20 knots. You come down to 500 feet and you cross into the sheltered, low-wind, surface air—or worse, blowing in the opposite direction. Your airspeed has suddenly dropped by 20 knots, easily enough to make you stall, since you were slowing down to land. This is called wind shear. It can be deadly.

Besides wind, there are other aspects of weather that make flying, not just landing, hazardous. The most common is simply clouds, haze and fog.

Flying into a mountain you didn't see because your windshield was a blank sheet of opalescent gray will ruin your whole day. Worse than that, if you are in a cloud or even flying over water on an overcast day where haze obscures the horizon, you can't tell if you are really rightside up or upside down. If you're upside down, you feel the same force on the seat of your pants; but it is because the airplane is actually accelerating downward at two G's. This is extremely unintuitive, and has caused quite a few accidents which the FAA euphemistically refers to as "controlled flight into terrain."

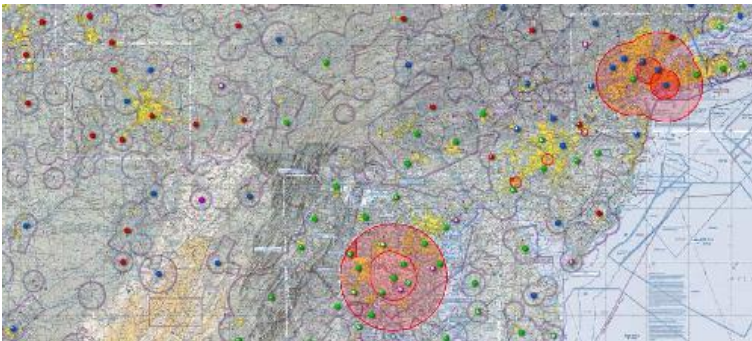
One of the harder things to learn about flying is to trust your instruments instead of your instincts.

Ice can form in your carburetor, choking your engine; it can form on the wings, destroying their lift, or freeze the control surfaces with disastrous results. The violent winds in thunderstorms can toss you around like a leaf. Highway traffic is susceptible to fog, storms, and ice as well, but not as often as air traffic. On the other hand, modern airliners routinely fly over weather, or around big storms, instead of through it.

Thin Air

Flying high has its own dangers, however. In particular, anoxia can sneak up on you, resulting in a condition that is like being very drunk without realizing it. This is magnified if you have even a little alcohol in your bloodstream; drinking and driving is a bad idea, but drinking and flying is a *very* bad idea. On a long flight, dehydration can cause some of the same symptoms, and thin air can dry you out a lot quicker than you realize. You need to watch out for this on an airliner flight as well; the cabin pressure is kept at the equivalent of 9000 feet (7000 in some newer airliners). A small plane with normally aspirated (i.e. not turbocharged) engine can have a service ceiling in the neighborhood of 14,000 feet, high enough for you to need supplemental oxygen if you're up there very long. Put more engine in it and you're definitely going to need oxygen or a pressurized cabin.

... and other hazards to flight



This rendition of FAA sectional charts plus real-time data, courtesy of the invaluable website skyvector.com, gives an example of the things a flier has

to look out for. The colored dots indicate the weather reports for airports with weather stations. Green means VFR (visual flight rules) conditions, i.e. the ceiling is high enough and visibility is far enough to fly safely simply by looking out the windshield. If there's a white spot on the green dot, the sky is actually clear, it's nice flying weather, fit for going up for a joyride. Note that only three of the stations on the map qualify (Ocean City, Manassas, and Gaithersburg). Blue means it's legal to fly visually, but the conditions are marginal (and in practice, could easily worsen). Red is IFR (instrument) conditions, which means you can't see out, and so must rely on your instruments to avoid flying into the ground, and on air traffic control to keep from hitting other planes. Purple means even worse than that. (A white spot on a purple dot, *e.g.* Cape May, usually means the weather report is incomplete or inconsistent, but could also mean ground fog under a clear sky.) This is, of course, the planet Earth, but there appears to be a Great Red Spot. Instead of a Jovian storm, it is the SFRA (special flight rules area) which is in effect a no-fly zone over Washington, DC. The similar blob over New York is a TFR (temporary flight restriction) because the President is traveling there on the particular day, and the other little red circles scattered in between are also for VIP travel. Only one of the 10 active TFRs shown is for physical flight hazards.

Neither snow nor rain nor heat nor gloom of night

“Time to spare? Go by air!” is the wry quip of the VFR (visual flight rules) pilot attempting to use his airplane as a touring vehicle. By far the biggest drawback to flying as a means of travel is weather. If you are equipped (and licensed) to fly on instruments, i.e. without any visibility out the window at all, and have an airplane that is capable of resisting ice formation, your windows of flying opportunity are somewhat closer to those of commercial airliners. Otherwise it is not uncommon to get stuck somewhere and just have to wait the weather out. If only you could drive the airplane on the highway...

Air Traffic Control

“Smallville Ground, Toyota six five four echo bravo charlie at seven seven three Elm Street, taxi for interstate niner five south with information golf.” You have gotten into your car and are about to drive to Aunt Millie’s house for tea. Since your home is in “controlled groundspace,” you cannot simply pull out into the street, but must contact Ground Traffic Control for clearance. Your Toyota’s license plate is 654-EBC. You speak in a cryptic code to save radio time, since everyone in town uses the same frequency. You have to verbally identify who you’re talking to, who you are, where you are, and what you want to do. You tell the controller that you already have the weather report so he doesn’t have to read it to you over the air.

“Toyota echo bravo charlie, Smallville Ground, altimeter two niner niner two, proceed Elm Street south, Nathan Alley west, Fairmont Way south, hold short of Market Street.”

You now have right of way up to Market Street, where you must stop. You also have to acknowledge that you heard the stop instruction:

“Echo bravo charlie, hold short of Market Street.” You can add “Roger” if radio traffic is light.

And so you proceed across town to the freeway, asking and getting clearance every few intersections. Finally you switch frequencies to a different controller:

“Smallville Tower, Toyota six five four echo bravo charlie ready for departure at interstate niner five south ramp one six seven bravo, request left lane.”

After a wait to allow a few big trucks to go by, “Toyota echo bravo charlie, cleared for departure, continue right lane until advised.”

“Echo bravo charlie.”

Now you’re on the highway and need to take the Middleburg bypass.

“Toyota echo bravo charlie, contact Middleburg Approach on one two three point four five.”

You toggle in yet another frequency on your radio.

“Middleburg Approach, Toyota six five four echo bravo charlie checking in.”

“Toyota six five four echo bravo charlie, squawk four three four two and ident.”

This is a setting for your radar transponder, which tells the controller your altitude.

“Toyota six five four echo bravo charlie, altimeter two niner niner two, maintain course at three thousand.”

Your altimeter is essentially a barometer that reads out in feet above sea level. But barometric pressure is always changing, which is why we use it to predict weather. You have to keep yours calibrated to whatever the sea-level pressure would be wherever you are. Controllers will provide you with the setting you need; if you are flying VFR, i.e. not under a controller, you are well advised to tune to every nearby airport you pass and pick up their altimeter settings.

There is in fact quite a lot of the airspace around the country where you can fly however and wherever you want (in good weather). The reason for air traffic control, or for using the radio in uncontrolled airspace, is to avoid accidents: collisions or near-misses where the wake of a big jet can tumble a light plane out of the sky. The ground controller at a big airport (after which I modelled the town traffic controller above) is necessary because virtually all the runways and taxiways are one-lane roads and airplanes can’t back up. (They don’t even have rear-view mirrors.)

But the main reason all that radiocom is necessary is that airplanes in the air are surprisingly hard to see. This is unintuitive because even a small plane is a fairly large object in everyday terms—it’s generally about 30 feet wide. But the plane you’re looking for is typically miles away. When you watch out for traffic on the road, you’re looking for a car that may be 100 feet away. The area of the airplane as a spot on your retina could be 10,000 times smaller than the car. What’s more, the plane can be anywhere against a cluttered background, whereas the car will appear in a relatively circumscribed, predictable area.

Add to that the fact that you might have some clouds, the far distance is usually hazy even on an apparently clear day, and that closing speeds can be several hundred miles per hour, and you can see why being on the radio is a good idea.

“Toyota six five four echo bravo charlie: radar service terminated; squawk VFR. Frequency change approved. Good day!”

——Bottom Line——

For most gulls, it is not flying that matters, but eating. For this gull, though, it was not eating that mattered, but flight.

—Richard Bach, *Jonathon Livingston Seagull*

From the Accomack County, Virginia, airport to the general aviation airport at Colonial Williamsburg is 52 nautical miles as the crow flies. My airplane does that at normal cruising speed in something under half an hour. It is a pleasant excursion on a nice day to fly to Williamsburg, have lunch, and fly back. Driving to Williamsburg takes more than two hours each way, including crossing the Cheapeake Bay Bridge/Tunnel (\$18 toll). A little further in the opposite direction is the Georgetown, Delaware, airport. Both of these, and several others in the same general area around the Bay, are nice lunch destinations because they have decent restaurants, catering to pilots doing just this, at the airports.

The phrase “hundred-dollar hamburger” is common among pilots and aviation writers, and it is a wry comment on something. It’s not quite so clear what the something is. After all, anyone who has put in the money and effort to be able to fly isn’t really going to be objecting to flying. It seems more likely an expression of an annoyance that the best excuse you can find for flying is to go out to lunch. General aviation today is so circumscribed as to be essentially a very expensive hobby and not a useful mode of transportation.

Aviation as a whole has a major last-mile problem. We pilots might gripe about hundred-dollar hamburgers, but commercial aviation is far worse. Imagine that you were trying to take an airline flight to go to lunch, complete with reservations, ticketing, security lines and X-ray scans, making sure you weren’t accidentally carrying a pocket knife or bottle of water, gate changes, waiting in line at the gate in boarding group 7, waiting to debark while everyone in front of you struggled with their carryons in the overhead compartments (and just forget checked luggage), getting a rental car, and so forth. Twice. If you tried to fly to lunch commercially, even if

the actual flight itself were instantaneous, you would do nothing else that day.

From the point of view of general aviation, “so near but yet so far” describes it best. The hundred-dollar hamburger gives us a taste, so to speak, of what the world could be like with flying cars.

11 Dialogue Concerning the Two Great Systems of the World

Ever since *Green Light for the Age of Miracles* told us that there might be cars with wings *and* helicopter flivvers in the Postwar World, the notion of the flying car has been bifurcated into two major categories, which we will refer to as convertibles and VTOLs.

Helicopters



Who needs a runway? A Robinson R44 in New Zealand, which has more helicopters per capita than any other country.

By far the closest you can come in the real world to the experience of a personal flying car as expected by the science fiction writers and pundits of the post-war world is a small helicopter. The Robinson R44, pictured, has about the same total weight, interior size, useful load, cruise speed, and operational ceiling as my airplane. They have similar engines, the workhorse Lycoming air-cooled horizontally opposed aero engine, but mine is a 4-cylinder while the R44 sports a 6. The only big difference, flying, is that my fixed-wing airplane has about twice the range of the helicopter. But of course the real difference isn't in flying; it's taking off and landing. Instead of thousands of feet of runway, 50 to 100 feet wide, the helicopter only needs a 10 by 10 foot pad. The amount of land taken up is little enough that most hospitals, and many high-end resorts, corporate headquarters, and snooty wineries have them, even though the amount of traffic is typically small.

Taking off in a helicopter is a much more civilized proposition than in an airplane. Instead of taxiing out to the end of a runway, lining up, shoving the throttle to max and careening down the runway, you simply sit there while the motor runs the rotor up to speed. Then you tilt the wings for lift, just as you do the airplane—except that in the airplane this involves tilting the entire airplane, but in the helicopter only the rotor blades tilt. So your

seat just moves smoothly up like some improbable stair lift. The vehicle accelerates once it's in the air, but that can be as fast or slow as you like. That is, as a passenger. To the pilot, flying a helicopter is somewhat more complicated. The energy chain, engine - speed - altitude, has one more link, rotor speed, and the relationships between the links are more complex.

(That said, overall energy management is more like an airplane than you might think: you're still best off climbing out and approaching at a fairly shallow angle, for example.) Controlling the helicopter is much more demanding: the machine as a whole is unstable, the gyroscopic dynamics of the rotor are non-intuitive, and there is a lag between control input and response. In an airplane you can take your hands off the controls and the plane will more or less keep doing what it was doing, but flying the heli is more like standing on a beach ball, especially when hovering. Incidentally, the helicopter controls are typically somewhat reversed from those of an airplane: the throttle is in your left hand instead of your right, and the stick that controls roll and pitch is in your right hand instead of your left. (The foot pedals control yaw in both cases.) This is not perversity; the set of reflexes you need to develop is different enough that you are much better off learning completely different ones than instinctively doing the wrong thing when you have to act quickly without time to think.

Add to that the fact that the helicopter is mechanically much more complex than an airplane. A simple airplane is just a glider, an engine, and an interestingly carved stick, the propeller. The rotor blades on the helicopter are typically individually hinged, flapped, and tilted; the pilot has a collective control that causes all of them to increase angle of attack, and a cyclic control that increases angle of attack on one side and reduces it on the other, in any direction and to any desired degree. All while rotating and exerting enormous centrifugal forces on the hub. What's more, there is a secondary driveshaft from the engine that runs the tail rotor, and it too has collective pitch, controlled by the foot pedals.

And even that is something of a compromise; at cruising speed, the two-bladed rotor develops a "two-per" (revolution) vibration which, while easy enough to get used to, keeps the ride from being as smooth as it could be (it feels about like having a slightly unbalanced tire in a car), and makes the craft less stable in flight. A four-bladed rotor would be a big plus.

So it is not surprising that a helicopter needs more engine, more piloting skill, a lot more maintenance, and costs more than an airplane. But the advantages are such that it was not at all unreasonable for the science fiction writers to have imagined them developing into generally-used flying cars. We can get something of a handle on the balance of technical to economic factors by noting that the sector of our economy most flush with cash, health care, has substantially higher helicopter use than the rest. Virtually every hospital has a heliport.

Helicopters today are perfectly capable of the quantum jump in convenience we would like in our flying cars. Perhaps the most unexpected of the revelations I learned in the research for this book was how close the speed and load capabilities of a small helicopter were to those of a small airplane. By far the major drawback to a helicopter is cost; difficulty of piloting is a distant second.

Today, new helicopters are in the \$1 to \$10 million range, and used ones can be had for \$100 thousand to \$1 million. This is similar to the range for private jets; small piston planes are five times cheaper in both categories. Aircraft engines are quite expensive to begin with; they have to be high-power and high-reliability at the same time as being low-weight, which is a major engineering challenge. Helicopter engines are the same only more so. A new Lycoming IO-540-AE1A5, as used in the Robinson R44, lists at \$118,481. Most helicopters simply use turbines, putting them in the same class, pricewise, as jets. (The piston-powered Robinsons are in the \$3-400,000 range; the Guimbal Cabri G2, Robinson's main competitor for the small heli market, lists for \$410,000.) What you pay for the VTOL capability of the helicopter isn't just money; it's an engineering tradeoff that includes low top speed and high fuel costs per mile. Put the same engine in, say, a Mooney M20, and you get an airplane that can do 250 instead of 100 knots.

Technologically, the helicopter speed limit works like this: when the helicopter is hovering, the rotor blades are moving at the same speed through the air, and all you have to worry about is keeping the blade tips subsonic; going supersonic would create a huge amount of noise, shockwave disturbance, and waste power copiously. Once the helicopter is in motion, however, the blade on one side is moving forward, the advancing blade, and has the vehicle's speed added to its rotational airspeed, and the

opposite, retreating blade, has the vehicle's speed subtracted. The faster you go, the greater the difference. But that puts your aerodynamic properties in a vise: your advancing blade is pushed against the sound barrier, and your retreating blade is pushed against going too slow to generate lift. So the basic standard helicopter design is pretty much limited to about 125 knots.

Autogyros

A usable helicopter in the family-car class, e.g. the Robinson R44, needs about 200 horsepower (250 at takeoff). That much engine in an autogyro gets you a slightly faster machine: technically, the rotor is less loaded because it is only providing lift instead of lift and propulsion, and so retreating blade stall sets in later. The experimental testbed "Cartercopter" gyro gets up into the 150 mph range, as did the 1990s Groen Aviation Hawk 4 4-seater. The gyro, if properly designed and expertly piloted, can land on a dime, but needs a short (200 feet) takeoff roll. [\[147\]](#) That is a very short city block, or two tennis courts, or the width of a square 1-acre lot. Back in the 30's, barnstorming autogyros used to land in, and take off from, football stadiums, with room to do a climb-out over the stands.

Gyros that could take off vertically were built in the Thirties, notably Pitcairn's last model, the PA-36 Whirlwing. The rotor was run up to about 150% cruising RPM by the pre-rotator, and then collective pitch applied. This could produce a one-time hop of about 20 feet, from which the gyro could fly off normally. The mechanism necessary for this, however, made the machine as complex as a helicopter, and the takeoff was a demanding and somewhat dangerous procedure.

The simplest way to get vertical takeoff with a gyro, in situations where you can't afford even a quarter acre of land, would be to put in a big stationary fan to produce a 25-knot headwind. You wouldn't need more than about 250 HP, i.e. a small truck engine; the whole thing could be pretty cheap. And you wouldn't need it for landing at all, meaning that it wouldn't have to be built to aircraft standards. Landings are mandatory, but takeoffs are optional.

The major technical innovation in gyros since their heyday in the Thirties has been the invention of the "teeter hub" one-piece rotor by Igor Bensen in the Fifties. A lot of the complexity, and thus expense, of the rotor hub on

both helicopters and autogyros was the fact that each blade had to be individually hinged both up/down and forward/back, and that the hinge had to withstand the enormous centrifugal force while remaining extremely precise with no play or looseness. Bensen realized that if there were only two blades, the hinged excursions of one were just opposite those of the other one. This includes not only the up/down flapping, but the forward/back precession, and indeed the cyclic angle of attack variation. The way this works is ingenious but mechanically simple, so the rotor can be one solid piece without the centrifugal force going through linkages, hinges, and bearings. This substantially lowers the cost and raises the reliability of the gyro. Unfortunately, you can't use Benson's trick for a helicopter (or a jump-takeoff gyro), because it doesn't allow for collective pitch control.



The author with a modern AutoGyro. Note that while the rotor can teeter like a seesaw, it is one solid piece.

There has been something of a resurgence of gyros in recent years, particularly in Europe, using the Bensen-style teeter hub and with a small enough engine to fit in a light-sport category (and be relatively inexpensive). They are fun machines to fly but don't have as short a takeoff roll as the Pitcairn gyros. The Pitcairns had three times as powerful an engine, and would pre-rotate the rotor up to full flying speed before moving. The modern light-sport types use a lighter mechanism to bring it

up to half speed and use the takeoff roll to bring it up the rest of the way. But they can still land on a dime.

The gyro continues to be the compromise between the airplane and the helicopter, along a number of different dimensions, including cost, runway area, flight performance, and training requirements. It can be a lot less expensive, and is easier to make roadable. The economic tradeoff would depend on the relative costs of land (or roof decks) compared to machinery. That has shifted from favoring autogyros toward favoring helicopters since the Thirties, but if we had had a flying car economy there would still probably be a good number of gyros around.

So there is a spectrum between the two extremes. But at the extremes, you will pay as much for a helicopter as you would for an airplane that could go twice as fast. Is it worth it?

The Value of Travel

A horse! A horse! My kingdom for a horse!

—Shakespeare, *Richard III*

Many years ago, when I was working at Rutgers, the University built a new office building next to the one I was in. The space they used was the parking lot at my building, so everyone had to park in the larger, further lot beyond the new building. Not only was this farther away, but with the people from the new building using the same lot, one was more likely, on average, to find the open spaces on the outer edges of the big lot. The result was to convert a 100-foot walk from car to door, taking about 20 seconds, to a 600-foot one taking 2 minutes.

As an experiment, I bought a folding bicycle to commute from my car to the office building. This was a simple, single-speed machine, but I found I could travel about 4 times faster, with the same level of effort and comfort as walking: 20 feet per second as compared with 5. This reduced my transit time to about half a minute, not too much worse than it had been before. It should be clear that the success of this venture depended critically on how long it took to get the bike out of the car and unfold it. It turns out that it was small enough not to need to fold it in the office, but just lean it against the wall. This was inside my office, of course; the moral fabric of our great universities is such that the half-life of an unattended bicycle is about 20 minutes. But my simple folding bike, slow as it was compared to a “real” bicycle, assembled in less than five seconds. Indeed, with a little practice, it took no more time than picking it up out of the car and putting it on the ground. You simply grabbed it in the right spots, lifted and twisted at the same time, and put it down with an extra nudge to make it click. So I was saving at least a minute with each trip to or from my car. With four trips a day (to and from work, and to and from lunch), this adds up, somewhat surprisingly, to 20 hours over the course of a year.

Once I got to the office, by the way, I spent much of my time working on parallel computer architectures. I mention this because there was a saying in

the field, originally a quip by Carnegie Mellon's H. T. Kung: "Any idiot can get throughput. What's hard is latency."

The lesson for a flying car designer should be clear. A classic convertible plane, such as the Aerocar which took 15 minutes to convert between modes, can't fly anywhere in less than half an hour. If you add a fifteen-minute drive to and from the airport, you can't go anywhere in less than an hour, which pretty much kills any pretensions you had to being a convenient form of travel.

There have been two major approaches to the flying car, which we will refer to as convertibles and VTOLs. Convertibles fit better with already existing infrastructure; if you could buy one now you could use it immediately. For a VTOL (say you just bought a helicopter), you would need to put a helipad in your back yard. You'd also need for each friend or business you were visiting to have put one in too. On the other hand, helipads are pretty simple: for a start, clear a 35-foot circle of ground—it doesn't even have to be paved. If there were a clear trend toward VTOL ownership, even if penetration were only 1%, homeowners and businesses would start putting them in as status symbols.

A convertible VTOL would allow you to drive to the nearest 35-foot clearing, take off, and do similarly on landing. The turnaround loop at the end of most residential cul-de-sacs is easily big enough, as are most parking lots. The convertible VTOL would provide the best of both worlds, but necessarily would be the most expensive.

If 1% of cars were convertible airplanes, it would put a major strain on the existing airport and airspace infrastructure. We shall consider air traffic control later, since it is roughly the same for both kinds of flying cars; but existing public-use airports would quickly become high-traffic chokepoints, both in the air and on the ground. New airports would involve a major public infrastructure investment, which would probably form the limiting factor to flying car adoption.

The second point of difference is convenience versus trip length. VTOLs are better for short trips: you don't have to go out of your way to two intermediate airports, and you don't have to stop to extend and retract the wings. A not unreasonable estimate is that a convertible would take an extra 45 minutes for any trip where it flew. On the other hand, the convertible, all other things such as price and technological sophistication being equal, will

be faster in the air, and thus better for trips above a certain length. Furthermore, it doesn't have to fly, so for short trips it has the same times as a car. Let's see what trips look like if the VTOL has an airspeed of 100 knots and the convertible 250. Just for fun, I have added a column for an imaginary, utopian fast VTOL which only has 2 minutes of overhead time and does 475 kts enroute.

Place	miles	Car	Conv.	VTOL	FVTOL
Downtown	7	:17	:17	:02	:02
airport	11	:23	:23	:03	:03
next town	19	:32	:32	:10	:04
Ocean City	74	1:32	:58	:37	:09
Williamsburg	117	2:16	:58	:37	:09
Williamsport	344	6:11	1:38	1:38	:29
Nashville	769	11:35	2:48	5:15	1:06
Wichita	1421	20:55	4:52	10:15	2:09
Palo Alto	3016	44:00	9:29	22:20	4:36

Miles are statute miles along the roads; as-the-crow-flies air miles are typically about two thirds the distance. The road system is apparently close enough to fractal that this seems to hold true at all scales. Perhaps as a result, even the slow VTOL wins spectacularly over a car, and is only beat by the convertible for trips of 300 miles or more.

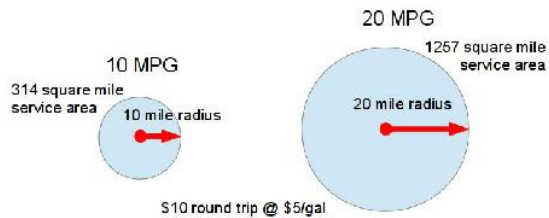
It wins, that is, for all the short trips of the kind you make now in your car. But what about the kinds of trips you would make if you actually had a flying car? Wouldn't you make more long trips? Jevons' Paradox might hold, with time efficiency standing in for fuel efficiency.

Jevons' Paradox

It's generally considered proper for someone who is environmentally concerned to be in favor of energy efficiency. Green organizations are major supporters of CAFE standards for higher gas mileage cars, and higher lumens-per-watt light bulbs. But you might be surprised to learn that power and energy companies are in favor of these things too, because they know something that the greens tend not to think about: historically, the more

efficiently energy has been used, the *more*, not less, total energy has been consumed.

This apparent paradox was first noted by economist William Stanley Jevons in 1856 in his book *The Coal Question*. The historical fact that he noted was that when the steam engine became more efficient with the introduction of James Watt's separate condenser (and many other improvements), the amount of coal used in England grew rather than declining. What this meant was, of course, that people were using the new, efficient Watt engines to do many more things than they had been using the older, less efficient, Newcomen engines to do.



Let's take a simple example. Suppose you are a farmer who sells tomatoes. You have a truck that gets 10 miles to the gallon. A gallon of gas costs, say, \$5. If you deliver a truckload of tomatoes to a market 10 miles away, the round trip costs you \$10. Let us further suppose that that is as much as you can spend on gas and break even on your tomatoes. You can sell tomatoes to anyone less than ten miles away but not to anyone further.

Now suppose a truck becomes available that gets 20 miles to the gallon. You can now afford to deliver tomatoes up to 20 miles away for the same amount of gas. But notice: a circle with a 20-mile radius has four times the area of one with a 10-mile radius. All other things being equal, you have four times as many viable customers with the new truck. So although the new truck only uses half the gas for any given specific trip, you are making four times as many trips, *and* each trip is twice as long, on average, as the ones you were making before. So you wind up using four times as much gas as you did before!

In practice, of course, other constraints, such as the amount of time or tomatoes you have, will weigh into the equation. But it should be clear that there are situations where efficiency will tend to increase energy usage. And

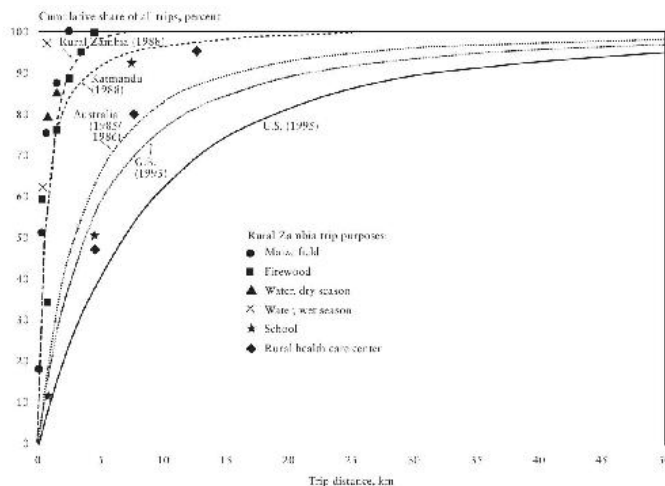
indeed, that has been the general historical trend. More to the point, one of the most salient costs of transportation is time; at prevailing wages, speeds, fuel efficiencies, and gas prices, the average American pays 10 cents for gasoline for each mile travelled, but spends 50 cents worth of time. The essential thing to note about Jevons' Paradox is not that people are using more energy; it is that they are getting *more total value* than the mere price reduction would have predicted. More people get tomatoes; the farmer makes more money; so does the gas company. Everybody is better off.

Travel theory

Everything in New Jersey is 20 minutes away.

—popular saying there

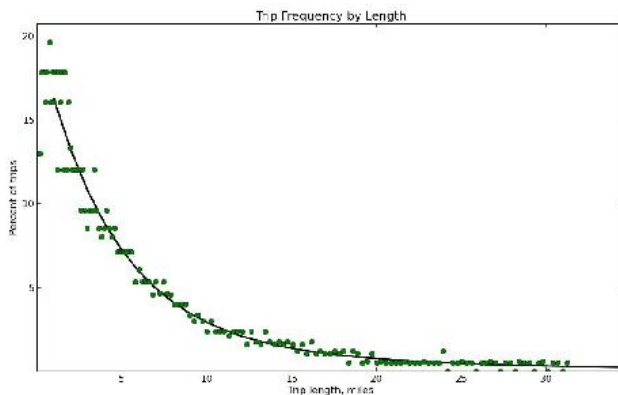
It is somewhat surprising, but to a certain extent we can calculate just how much it would be worth to have flying cars of various types. There is a research literature in travel theory, which is the study of how much people travel in various environments in different modes. It is mostly used in road and transit planning, but it gives us data and a point of departure. Here is the kind of thing you will find: this graph shows that as long-distance travel becomes more convenient, people do more of it: [\[148\]](#)



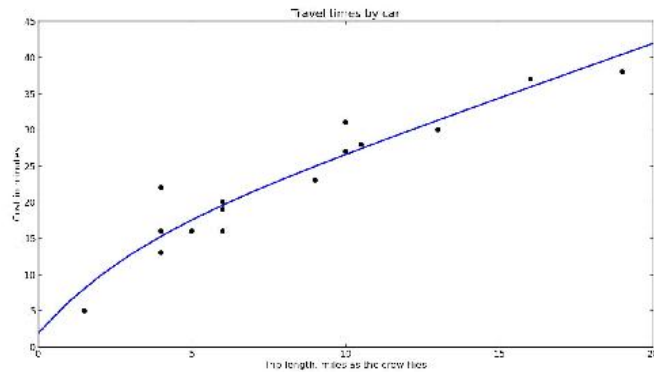
One would expect that if flying cars were available, people would make even more, even longer trips. But the surprising, unexpected empirical

finding from travel studies is that people in all these societies spend about an hour a day travelling, whether they are in Zambia walking barefoot or in the US riding in an air-conditioned car. Some people travel a lot more than others within a given society, of course, but the average across a given a society is just over an hour—apparently a human universal.

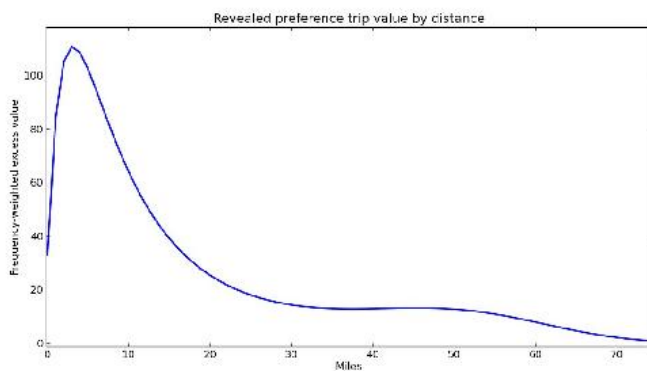
To get a handle on how much people might travel under situations more advanced than ours, we can fit a curve to the data and extrapolate to longer trips and use it in calculations for faster transport modes:



For Americans, this is almost entirely by car. It turns out that there is another more-or-less surprising universal: your car does 40 MPH. For virtually any trip, of any length, the effective speed of a car as measured by the time taken to go the point-to-point distance as the crow flies is 40. You might think that you could do better for a long trip where you can get on the highway and go a long way fast; but again, the road system is essentially fractal. The big highways, on the average, take you out of your way by an amount that is proportional to the distance you are trying to go:

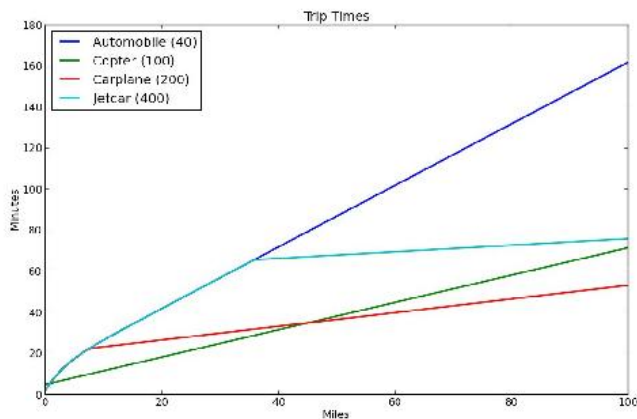


Now the really interesting thing is that we can combine these two functions and derive the value to the average American, as measured in the amount of time they are willing to spend, of getting to whatever destinations there may be at a given distance from where they live:

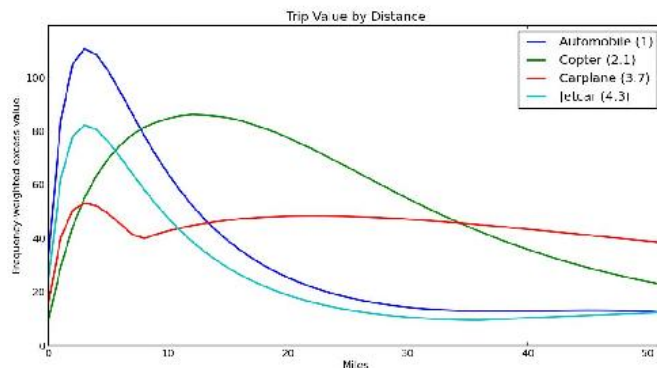


There are two features of this graph that have at least intuitive explanations. The first is the peak in trips under ten miles. This is due to a combination of the low (time) cost of such trips, and a shadowing effect. If there is a McDonalds 5 miles from your house, you aren't going to go to one 10 miles away. To the extent that many destinations are alike, the near ones "shadow" the value of the far ones. The other interesting feature is the sort of hump going out to 50 miles. This is probably a daytrip phenomenon, together with the kinds of destinations for which people will make a trip of that length: a ballpark, a hospital, a restaurant fancy enough for an anniversary, etc. But in any case this is the empirically determined value to people, as revealed by their willingness to make the trip, of destinations at various distances.

Now we can design some flying cars—at least specify how close to home they can take off and how fast they can go. Let's take three designs to cover the spectrum: a helicopter-like one that lands in the driveway but can only do 100 knots; a convertible airplane that can do 200 and land on a short private strip or straight stretch of road; and a jetcar that can do 400 but has to be flown out of a full-fledged airport. Here's how they compare with a car, noticing that for many short trips with the latter two you never take off at all but just use them in car mode:

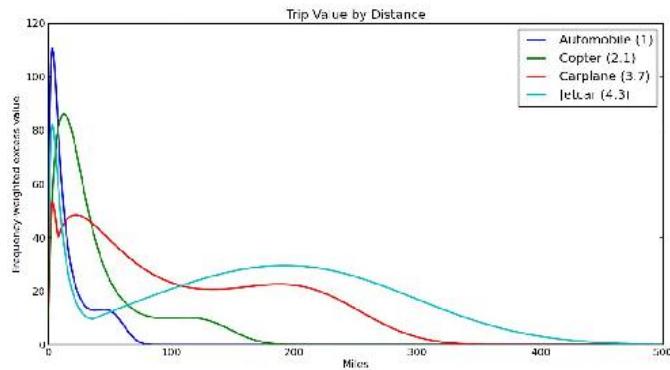


The next step is to substitute these travel times back into the value equations and find out how people would travel differently with flying cars of these types, and how much it would be worth to them. At short distances, the helicopter (or pure VTOL) dominates:



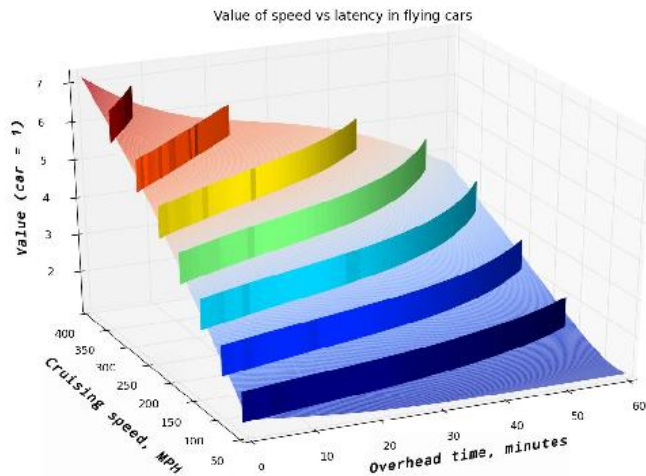
(Note that for these distances, you never actually fly the jetcar!)

This is the obvious advantage to a flying car, and the one most people are thinking of when they imagine a VTOL type: the ability to make the kinds of trips you normally do make, faster. But perhaps surprisingly, the numbers show that that's not where the major value would actually be:

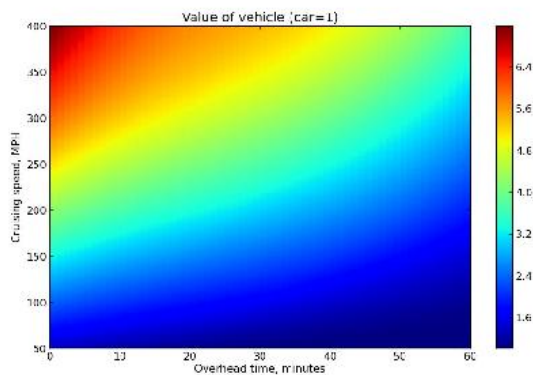


When you look at longer distances, the jetcar dominates. The difference is that you would make a *lot* more long trips than you do now. Jevons rules. These are higher value trips but are too expensive in time to make very often with a ground car. Note that the value of having the given vehicle, as compared with a car, can be determined by taking the total area under the curves. The reason that the curves for the flying cars appear to represent less value for trips less than 20 miles or so is that you'd be taking fewer trips under 20 miles if you had a flying car—you'd be taking longer ones that were of more value to you instead.

We are now in a position to evaluate the value of any flying car, at least as specified by a latency number (the number of minutes added to a trip by having to go to an airport, convert car to plane, etc.) and a speed. The result is expressed as a multiple of the value of having a ground car:



Value of a flying car represented as a multiple of the value of a ground car, as a function of speed and latency (overhead time per trip).



The same chart, in a more easily read-out-able form.

A jetcar that was a VTOL you could fly from your driveway and make long trips at 400 MPH would be worth 7 times as much as an ordinary groundcar. The jetcar in the previous graphs, the convertible that did 400 but had an overhead of an hour per trip, has about half that value, 3.5 times that of a car. A fast prop-driven convertible (250 mph) would be about 2.5 times as valuable as a car, and a slow one (100 mph) only about 1.4, if they had to be flown from airports. That's roughly the same increment to the value of a car that you get from being able to drive to an airport and fly commercially at 400 knots, but incur a three-hour overhead in addition to actual flying time.

In theory if you would pay today's average of \$35,000 for a groundcar, a fast VTOL jet car you could fly from your driveway would be worth \$245,000, as far as pure travel time value is concerned. Its value as a status symbol remains to be seen.

——Bottom Line——

Any ordinary, active man, provided he has reasonably good eyesight and nerve, can fly, and fly well. If he has nerve enough to drive an automobile through the streets of a large city, and perhaps argue with a policeman on the question of speed limits, he can take himself off the ground in an airplane, and also land—a thing vastly more difficult and dangerous.

—Sweetser and Lamont, *Opportunities in Aviation* (1920)

The gyro community is doing superbly ... everywhere but in the USA.

—Light Aircraft Manufacturers Association

Zimmerman, Custer, La Cierva, and Pitcairn were right: the inability to fly low and slow, for safety but even more importantly to takeoff and land in small spaces, were major impediments to the general adoption of private flying machines. Taking off and flying an airplane is not that much harder than driving a car, although landing is, particularly in rough weather. But any reasonably coordinated person can learn to fly with 50 to 100 hours of training and practice.

Flying in small private aircraft is less comfortable and scarier than ground cars. On the other hand, flying in airliners, or even private jets, is something almost everyone can handle. There is a continuum both in people and in machines. The helicopter and the autogyro are more stable in gusty air for exactly the same reason that jets are: high wing loading. Besides simply being smaller and faster than an airplane's wings, the "wings" on a rotorcraft are always moving in opposite directions at the same time, so a gust has less average effect — and the flapping automatically compensates for it.

Private aircraft were on a growth path up until the 80s, even under the restrictive regulatory regime.

In my personal experience, the necessity of using airports is by far the major drawback to the usefulness of airplanes. Flying a helicopter is

somewhat more difficult than an airplane, but again it is definitely a learnable skill. The helicopter solves many of the problems of the airplane, but it introduces enough mechanical complexity (and need for more power) that it costs as much as an airplane twice as fast. Even so, I can very easily imagine a technological trajectory in which ten percent of American families had a helicopter now. We could have been following the adoption of the car, just about a century later.

In 1910, the price of a Packard was about \$2500. By introducing mass production, Ford had brought that down to \$800 or so with the Model T. By the mid-20s, you could get a car for \$250. A Pitcairn PCA-2 autogyro cost \$15,000 in 1931, but by the end of the 30s, Pitcairn was selling gyros for under \$5000 (although probably at a loss). It seems not unlikely that with appropriate deregulation and mass production, the private aircraft industry could have been giving us affordable airplanes, and even helicopters, now. 75 years after Pitcairn we should have something at least as good as his autogyro. Gyros of perfectly usable specs are being built now. This is mostly in Europe, because the EU has an approved rotorcraft classification that is similar to the light-sport fixed-wings you can buy here, but the US does not. That means that in Europe, you can buy a gyro built in a factory, but if you want one here you have to build it yourself. A typical gyro goes for about a third the price of a helicopter and can use a 200-foot runway. The Dutch company PAL-V is in the process of launching a new design roadable autogyro. It has the same advantages as the Pitcairn designs of the 1930s, but updated with modern materials and technology. It also has to face a lot more regulatory hurdles, as a car as well as an aircraft, than there were in the 30s. As a result its roadable configuration is three-wheeled so that it comes under motorcycle regulations instead of car ones. The rotor, tail, and propeller retract and/or fold up and it becomes an enclosed trike-style motorcycle on the road. It's listed [\[149\]](#) at better than 100 mph both on the road and in the air.



The PAL-V ONE roadable autogyro.

Over the postwar period, the autogyro was very likely the technology of choice had we decided, as a society, to go for private flying cars. It would have enabled anyone with an acre lot to have their own landing strip, and it would have enabled many more people to have an acre lot. In fact in the Thirties, Eastern Airlines operated mail-carrying autogyros from the rooftop of the Philadelphia post office. The upward compatibility path to helicopters would have been straightforward when people started being able to afford them and to need that 10-foot helipad.

The main catch, of course, would have been air traffic control. Molt Taylor was right, too.

12 The Atomic Age

Should the research worker of the future discover some means of releasing this energy in a form which could be employed, the human race will have at its command powers beyond the dreams of scientific fiction.

—F. W. Aston, Nobel Lecture (1922)

Jim, you'll be interested to know that the Italian navigator has just landed in the new world.

—Arthur Compton to James Conant (1942)

The appliances of 2014 will have no electric cords, of course, for they will be powered by long-lived batteries running on radioisotopes. The isotopes will not be expensive for they will be by-products of the fission-power plants which, by 2014, will be supplying well over half the power needs of humanity.

—Isaac Asimov (1964)

It is often remarked that “future technology” as realized through the latter half of the 20th century leaned heavily to information processing — computers and Moore’s Law and communications and global networks— instead of heavy-duty, energy-using, transportation and construction and so forth of the kind that characterized the first half of the century. And the claim is often made that this was because there was a lot more technological headroom for information technology. For the past 50 years there has been no practical limit to the density, speed, and efficiency of information manipulation, and increasing cleverness has driven the state of the art in an unprecedented trajectory.

But, or so goes the argument, there are major physical limits to the big stuff. Moving matter around requires a certain amount of energy, period—and energy is expensive. Some people will go farther and argue that the

optimism and progress of the first half of the century was due to the rapidly expanding supply of cheap fossil fuel, and we ran out of that. But that doesn't work as an explanation for the divergence of science fiction predictions and what we actually managed to build. In *Profiles*, Clarke wrote:

But the gas engine is on its way out, as any petroleum geologist will assure you in his more unguarded moments. Before very much longer, out of sheer necessity, we must find some other source of power—perhaps a sophisticated type of battery, with at least a hundred times the capacity of today's clumsy monsters. [\[150\]](#) Whatever the answer, within a few more decades there will be lightweight, long-endurance motors of some kind, ready to take over when the oil wells run dry. These will power the private aircars of the future, as the gasoline engine has driven the earthbound automobiles of the past.

We don't have the batteries yet, but we do have the motors. He got the main point right: the future of energy is ingenuity. Recovery of fossil fuels is by no means the only source of abundant energy that technology can open up to us. Oil isn't free energy handed down from heaven. It took all of human technological development up until about a century and a half ago to be able to use it. There are other sources of energy just as plentiful—excuse me, more plentiful by orders of magnitude. It only takes developing the technology to harvest it.

We had already shifted from wood to coal, and from coal to oil, as our major energy source. George Jetson's car isn't going to fold up into a briefcase if its tanks are carrying 1000 pounds of jet fuel. There was a consensus among futurists and science fiction writers that the next shift was already beginning to happen, and we were on the verge of the Atomic Age.

Too Cheap to Meter

While you are boarding that 747-400 for your vacation in Australia, the ground crew will be filling its tanks with 57,285 gallons of jet fuel. [\[151\]](#) If you, like the average American, use about 500 gallons of gas in your car per year, that's enough fuel to last you 114 years. That amount of Jet-A weighs 194.6 tons, and the plane has to carry it, on average, half the flight—but in particular, has to take off and climb to altitude with all of it. In other words, if it didn't have to carry the fuel, the 747 could carry nearly 200 tons more passengers and/or cargo. Call it 1,946 people and their carry-ons; compare that to the typical 500 passengers 747s actually carry.

The energy produced by burning that much Jet-A fuel comes to 7.5 terajoules (TJ). The same amount of energy could be had by fissioning 94.3 grams (3.3 ounces, or a third of a cubic inch) of uranium.

The price for Jet-A, at a nearby airport as I write, is \$6.00/gallon. Fueling up a 747 would cost \$343,710 at that price. The commodity price of uranium, as yellowcake (U₃O₈) is \$49.50 per pound. Only 84.8% of yellowcake by weight is uranium, so the effective price is \$58.24, and our 7.5 TJ will cost \$8.66. Of course the 747 gets a quantity discount, and I have no idea what would happen if you tried to buy just 4 ounces of U₃O₈. But the point is clear: the amount of chemical energy you need to fly a 747 to Australia costs about a third of a million dollars, and the same energy as uranium is about ten bucks. [\[152\]](#)

One proviso, of course, is that less than one percent of natural uranium is immediately fissionable U²³⁵. But the potential energy is present in U²³⁸ as well. We don't burn crude oil in our jets; we process it into the fuels we need. There are other nuclear fuels, e.g. thorium, available as well. It all depends on the level of technology we can bring to bear.

Let's compare costs for a standard amount of energy. A terajoule (TJ) is the energy the average American uses in all forms (including your share of manufacturing, shipping, and worldwide military operations) in about 3 years. In the table below, the prices for gasoline, electricity, gas, and coal are consumer retail; the rest are commodity prices (they just don't seem to carry uranium at the local Walmart):

fuel	unit price	amount/TJ	\$/TJ
gasoline	\$3.37/gal	7,780 gal	26,000.00
electricity	\$0.12/kWh	278,000 kWh	33,000.00
natural gas	\$12.50/mcf	948 mcf	11,850.00
coal (anthracite)	\$170/ton	91,600 lbs	7,786.00
tritium	\$30,000/g	3.77 lbs	51 million
uranium (as U ₂ O ₈)	\$58.24/lb	0.028 lbs	1.40
uranium (enriched)	\$1.63/gram	12.58 g	20.00
thorium (oxide 99.9%)	\$0.20/gram	12.58 g	2.50
boron-11 (p-B fusion)	\$5/gram	15 g	76.00
lithium-7 (carbonate)	\$0.06/g	7.4 g	0.44
deuterium (heavy water)	\$600/liter	7.8 ml	4.00

Electricity, of course, isn't a fuel, but is included for comparison purposes. Consumer retail energy runs about five times the commodity price of the raw fuel, at a rough average. (The exception is that gasoline costs less than twice the price of the crude oil it's made from [\[153\]](#).) Most electricity in the US comes from coal or natural gas. With uranium, since it involves a costly isotopic enrichment step, the markup is more like a factor of 30. Even so, the cost of the uranium going into power generation is trivial compared to the other costs. We could reduce even that by a factor of ten by going to a thorium fuel cycle, but one of the main reasons that there hasn't been any major push to do that is that the uranium is already so cheap, on a per-kWh basis, that it's not worth the bother.

Average price of a year's energy, in chemical fuels: \$6,553. In nuclear, \$5.80. [\[154\]](#)

You can now understand why, at the dawn of the Atomic Age, some people might very reasonably imagine that when the technology was mature, nuclear-derived electricity might be “too cheap to meter.” Of course, “too cheap” is in some sense verbal sloppiness. It's not the absolute price of something that determines whether it makes sense to meter it, but the marginal price—what it costs you to generate one more kilowatt-hour, given that you've already built all the capital equipment and covered all the fixed overhead costs. It doesn't mean it's free, or even cheap—it just means you pay a flat fee, as you do for local phone service or basic cable.

But whether metered or not, if you just considered the raw fuel cost of uranium, energy from fission could be very cheap indeed. The cost of actual electricity delivered to your home is due to the cost of the capital—the reactor and generating plant, but also the transmission lines, substations, power grid control centers, and so forth—and overhead, including maintenance and a truly staggering regulatory burden that multiplies the cost by an order of magnitude. From this point of view, the cost structure of nuclear power is much more like that of solar or wind power than that of fossil fuels. The cost of “renewables” is essentially all capital and overhead as well.

If you look at the enormous energy available from nuclear reactions, you'll see that the notion that we have no technological headroom in energy is completely vacuous. A hip flask of heavy water, or a one-inch cube of uranium, contains more energy than the average American uses in a lifetime. Uranium provides 80 TJ of energy per kilogram; proton/boron-11 (sometimes called HB11) fusion 71; heavy water 128; pure light hydrogen, as burned in the Sun, 683. Gasoline provides 0.000 047 TJ per kilogram, while the “green” technologies such as LiPo batteries that have been receiving so much attention and investment recently give us less than 0.000 001. Or in terms of the amount of time one pound would sustain the average American at 10 kW, or the amount you would need for an 80-year lifetime:

Fuel	time / lb	lifetime
uranium	109 years	12 ounces

HB11 97 years 14 ounces

tritium 10 months 96 pounds

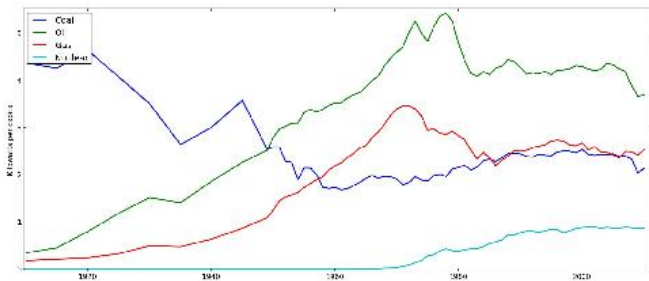
... as T_2O 82 days 351 pounds

gasoline 35 minutes 600 tons

LiPo battery 23 seconds 55,000 tons

Tritium is a completely synthetic isotope and is in current technology one of the most expensive substances that exist. I include it for comparison: used as a beta emitter, it falls somewhere between chemical and nuclear forms of energy storage. Its energy density is 0.583529 TJ per kilogram.

Let us look at the history of the Henry Adams Curve a little more closely. Over the past century, several stages in energy use have followed on each other as we shifted from one source to another. In the 1800s, wood was the major fuel; by 1900, as Adams noted, coal had taken off exponentially. As the Twentieth Century progressed, this was replaced by oil and natural gas.



Components of the Henry Adams Curve.

If you look at the overall total energy use, you can see that the Henry Adams Curve is a composite of a series of rises of the various successive dominant energy sources. Nuclear power took off from about 1960 to 1975. Did it have the potential to be the next one?

It certainly seems so; if it had only followed the same growth curve that gas did 1920-1970, by now nuclear would be producing essentially all of our electrical power. The question is, of course, where would the point of diminishing returns have set in for nuclear power? Fuel would not be the bottleneck, as it is for fossil fueled power. The rule of thumb is that nuclear fuels produce one to ten million times the energy per weight of chemical ones, and thus requires the extraction of a million times less raw material, and the production of a million times less ash, than fossil fuel for the same amount of energy. At the point where we were mining as much nuclear fuel as we are fossil fuel now, and thus spending as much for fuel as the current power industry, we would be generating a million times as much power. Presumably, we would long since have hit some other bottleneck.

Atomic number	element	abundance	\$/lb
1	hydrogen	1400	
6	carbon	200	\$0.03
28	nickel	84	\$7.54
29	copper	60	\$3.40
3	lithium	20	\$30.00
82	lead	14	\$0.84
5	boron	10	\$0.47
90	thorium	9.6	\$16.54
92	uranium	2.7	\$49.50
50	tin	2.3	\$8.75
47	silver	0.075	\$405.00

Thorium and uranium together are about 20 times rarer than carbon, so we might imagine that we would begin pressing on supply at about 50,000 times the energy we use today. Going by current-day prices, on the other hand, it might only be 1000. In either case, fuel costs are essentially trivial compared to fossil. The actual cost of power is all capital, actually even more so for nuclear than for so-called “sustainable” forms. A wind turbine uses up more lubricating oil than a nuclear plant uses uranium, per kilowatt-hour generated. [\[155\]](#) In practice the first bottleneck would be power transmission, to be ameliorated by smaller, more numerous, and mass-produced modular reactors. The second bottleneck would simply be that we didn’t have the ways and means to use that much power!

It is of course an extremely error-prone activity to speculate on what kind of advances might have been made in nuclear power conversion if a major, sustained effort had been made over the past 50 years. It is easy to dismiss the argument that there could have been a Moore’s Law for energy simply because the fuel is more energy-dense. The most commonly heard objection is that fission, and hot fusion, produce high-energy neutrons which are particularly nasty and require heavy shielding. But that implies that anywhere you wanted an engine you would have to put a fission reactor. But that is to commit a complete Failure of Nerve. It was well understood in the Sixties, perhaps even better than today, that you can create artificially radioactive isotopes of various elements by exposing them to neutrons (e.g., in a reactor). Typically the isotopes produced this way decay by beta emission, that is changing the extra neutron into a proton by firing off an energetic electron. Beta radiation can be blocked by a couple of inches of water or a thin sheet of metal (for average energies—the betas from tritium are stopped by a piece of paper). At the very least you could use the heat to produce power, which is after all what we do when we burn fossil fuels. Radioisotopic thermal generators had been introduced in the Eisenhower administration; but that is doing things the brute-force, inefficient way. “Beta rays” are after all nothing but energetic electrons. Back in the 70’s there was a betavoltaic battery, the Betacel, produced commercially.

Completely safe to handle and with a useful life of up to ten years, they were used in implantable pacemakers. Technologically, they use the high-energy electrons to create a trail of electron-hole pairs in an appropriate semiconductor device. One of the things that has improved a lot over the past 50 years is our semiconductor technology, so there has been a minor resurgence in betavoltaics in recent years. The best I've seen so far is a Russian lab prototype using a stack of Nickel-63 foils alternating with diamond Schottky-barrier diodes. [\[156\]](#) Calculations indicate that if optimized, it could have 50 times the energy density of a chemical battery, but the power is low, being delivered over the Nickel-63 halflife of 100 years.

It might even be the case that with 50 years of experience and experimentation, we could have come up with some way to stimulate useful kinds of radioactive decay in almost or very slightly radioactive isotopes. This would at the least give us heat-producing bricks that we could turn on and off. Our much more sophisticated electronics (and rare-earth and superconducting magnets) could surely produce more compact particle accelerators and X-ray sources (such as might be used to stimulate decay). Something like this would be necessary to replace the transport sector's fossil fuel use with nuclear; stationary applications like power generation could all be replaced with reactors. Current knowledge and practice puts the partition between the two. But we should have been pushing on it for the past half century.

Isaac Asimov's speculation—*The appliances of 2014 will have no electric cords, of course*—was completely reasonable, given the physics and the rate of technological improvement up until then. We really, really should have had atomic batteries by now. And guess what? Your iPhone would never need charging, and your Tesla would have a range of 3.5 million miles. *It is a possibility.*

One of the reasons that computers improved so rapidly in price/performance over the past half-century is that the physics of computation don't present the kind of "glass ceiling" that supersonic flight does for airplanes. (Another of course is that computers were essentially unregulated.) So the key to analyzing the question of how well reactors could have improved over the period is to see just what kind of headroom they had in the design space. Molten salt reactors using thorium and integral

fast reactors using uranium-plutonium alloys could achieve a 99% fuel burn-up, improving both fuel efficiency and waste production by a couple of orders of magnitude over the 1960s designs we're still using. Pilot programs showed encouraging progress toward each, with Oak Ridge operating a molten salt reactor (but without the full thorium fuel cycle) for a year or so, before being canceled. Fortune magazine (Feb 2015):

Nixon banished a reactor that was virtually meltdown-proof, left comparatively little long-lived waste, made it more difficult to fashion a bomb from the waste, ran at friendlier atmospheric pressure instead of the potentially explosive pressurized environments of conventional reactors, and ran at much higher temperatures, making it more cost-effective as an electricity generator.

Thorium is three to four times as common as uranium, and doesn't need the separate enrichment step—and the reactor could burn virtually all of it, rather than less than one percent. The result is that as a fuel, there is a few hundred times as much thorium available than uranium. Proven reserves of uranium could power the globe for 77 years; of thorium for 6472 years. Thorium is often present in coal as a trace impurity. Typically, there is as much energy present in the thorium—which just goes out the smokestack—as we get from burning the coal.

Molten-salt thorium reactors would have two major advantages over uranium ones, besides fuel availability: first, it's much harder to divert the fuel to make nuclear weapons. In fact that is one of the main reasons thorium reactors weren't developed in the Sixties. The U.S. government wanted a source of weaponizable uranium and plutonium. They went in with the mindset that we would control all the reactors and that the fuel cycle that gave us the bomb-grade stuff was a good idea. But that means that there has been a built-in block against making nuclear power generally available. The development of a thorium-based energy economy would make it much easier to proliferate power without proliferating weapons. The other main reason was also military in origin—it was simply that pressurized water reactors had been designed and developed for the Navy, and it was easier to copy and scale up in a bureaucratic regime where not innovating is always easier than innovating.

The second advantage is that a molten-salt reactor can be easily engineered to be walk-away safe. Existing designs (40 years old, because of the stagnation) for uranium reactors require continuous active cooling to prevent meltdown. But the fuel in the proposed thorium designs is already molten. If the power fails in a conventional reactor, separate emergency power is needed to run the cooling system. In the molten salt reactor, the design works the opposite way: cooling, enough to keep a plug of salt frozen, is powered by the reactor itself. If the reactor or generator fails, the plug melts, and the fuel flows into a sump where it's too spread out to maintain a reaction.

In other words, the physics of fission has at least a factor of 100 free upside in power/waste and is capable of using fuels that are 100 times as abundant as current practice. And remember that the fuel is cheap to begin with. The major problem with thorium as a nuclear fuel is, as mentioned, that uranium is too cheap already. All the cost is in regulatory compliance, and that would increase, rather than decrease, with an innovative new set of reactor designs and fuel cycles.

Atomic Angst

At some point in the last few centuries, human civilization had taken the wrong path—a path that led only to oblivion.

—Randall Garrett, *The Highest Treason*

“Decentralized cities, labor-saving machinery for everyone, luxuries—it’s all possible, but I’ve got a feeling that we’re staring right into a mess of trouble. Did you ever hear of ‘Breakages, Ltd’?”

“What is it, a salvage concern?”

“Not by a hell of a sight. It’s from the preface of Back to Methuselah, and is a sardonic way of describing the combined power of corporate industry to resist any change that might threaten their dividends. What do you think happened to atomic power?”

—Robert A. Heinlein, *Let There be Light*

At first sight, this manifestly suicidal neglect looks so perverse that a sheer inability to perform the work, owing to a loss of technique, might appear to be the only plausible explanation. Yet no historical evidence of this hypothetical loss of engineering technique appears to be forthcoming; and the true explanation seems to be that the abandonment of the works was not the cause but was rather the consequence of a decline in population and in prosperity which was itself the result of social causes.

—Toynbee, *A Study of History*

The faith in technology reflected in Golden Age SF and Space Age America wasn’t misplaced. What they got wrong was faith in our culture and bureaucratic arrangements. What L. Sprague de Camp called “The Heroic Age of American Invention,” of a century ago, had an accompanying chorus

of “they said it couldn’t be done” pundits, skeptics of everything from incandescent electric lights to airplanes, as paraded before the reader in Clarke’s *Profiles*. But the more centralized and bureaucratized science and technology has become, the more Failure of Nerve, much less Failure of the Imagination, produces not amusing mispredictions but official obstruction.

The Atomic Age was strangled in its cradle. The reasons are many and varied, but the bottom line is that technological progress has not run out of fruit; it has hit a glass ceiling. There is as much headroom in physics and engineering for energy as there is in computation; what is stopping us is not lack of technology but lack of will and good sense.

Perhaps the most pernicious of the memetic cancers to infect the public mind in the 70s was the nuclear hysteria industry. One of the best examples of just how pathological this remains even today is the reaction in the media to the incidents at the Fukushima I power plant in connection with the Tōhoku earthquake and tsunami in 2011. About sixteen thousand people died (most drowned), six thousand were injured, twenty-five hundred went missing. A quarter million were made homeless. 127,290 buildings were totally destroyed, 272,788 “half collapsed,” and another 747,989 partially damaged by the earthquake and tsunami. I repeat: all of this devastation was done by the earthquake and tsunami; it was a natural disaster of epic proportions. As part of all this devastation, the power plant was damaged and some radioactive materials were released into the local environment. How much danger did this release add to the overall cataclysm?

Zero. *No one* was killed by radiation exposure, and projections for excess cancer from accumulated exposure are negligible. [\[157\]](#)

So ask yourself: did the news coverage of the disaster reflect this risk ratio? Of course not. The coverage I saw was all hyperventilating about the power plant, but the thousands of people dying from natural causes were at best a footnote. Furthermore, the news reports greatly exaggerated the actual danger from radiation: [\[158\]](#)

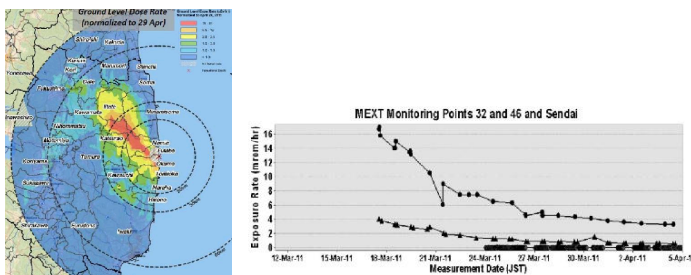
Readers who have closely followed Fukushima developments may find this story about the U.S. government’s worst-case scenario interesting though not necessarily conclusive. After all, didn’t the Japanese government draw up its own worst-case scenario? Indeed it

did. Didn't many news articles report that this scenario would have necessitated an evacuation of Tokyo? Indeed they did—wrongly.

The Japanese government, fully in the grip of the radiophobic hysteria, evacuated approximately 100,000 people from the vicinity of Fukushima to “protect” them from radiation levels about the same as the natural background in Finland. Some 1600 of the evacuees died from causes ranging from privation in refugee camps (notably loss of access to health care) to suicide. [\[159\]](#)

It is worth pointing out just how much harm and suffering the activists and the fear industry have caused in human terms. On the order of one percent of the evacuees in both Fukushima and Chernobyl committed suicide. This is something like 100 times the background suicide rate. You can imagine the increase in stress that had to accompany this—stress created intentionally by activists and the media for their own gain, prestige, and virtue signalling. This was by no means confined to the Fukushima area: there was a run on iodide tablets all over the US, to the extent that most suppliers ran out.

And then of course the media reported on the hysterical runnings around as if they were evidence of danger from radiation: the Japanese government uselessly scraped thousands of tons of topsoil from the plume area and stored it in photogenic piles of garbage bags labelled “nuclear waste.”



The Fukushima radiation plume. The red umbral region represents about 2 rem per year exposure, the yellow less than 1. For comparison, a typical medical CT scan produces an exposure of 1 rem; the NRC's annual exposure allowance for nuclear plant workers is 5 rem. This is for 2011, the year immediately following the release; by 2012 even this was mostly gone. (US DOE NNSA)

The actual measured dose over most of the release was less than having a couple of CT scans in a year. 1600 people died in vain, died not from radiation but from radiophobia.

This popular phobia of anything nuclear seems to be so deep-rooted that it must be classed with the great superstitions, such as the medieval belief in, and fear of, witches, with its attendant tragic immolations. Perhaps the only thing greater than the extent of the phobia, especially in the media, is the depth of complete, clueless ignorance of the subject. There appear to be two major emotional drivers for anti-nuclear angst: concern for the environment and for safety. The scare industry has for the most part unwitting accomplices in scientifically illiterate journalists who could not tell you the difference between a nuclide and a nucleotide.

You will never come to understand this from the hysterical media, but the fact is that nuclear power generation, even in the old pressurized or boiling water plants (i.e. the plants we still use) designed in the days when computers were built with discrete transistors and ferrite core memory, is the cleanest and safest form of power ever used on a non-trivial scale. [\[160\]](#)

Source	deaths/TWh	remarks
Coal (China)	280	air pollution: 500k /yr
Coal (world average)	170	
Coal (USA)	15	over 10k /yr in USA
Oil	36	think LA smog
~~strikeout off~~ <u>uuline off</u> ~~uwave~~ offBiofuels/Biomass	24	
Natural Gas	4	Cleaner than oil
Solar	0.44	falls from rooftops
Wind	0.15	
Hydro (China)	1.4	dam bursts
Hydro (US)	0.1	
Nuclear	0.04	including Chernobyl

Relative deadliness of the major energy sources. If you are thinking of splitting wood, not atoms, please remember that lumberjack is the number one most dangerous profession.

Greenpeace and other activist organizations pushed what has apparently become a widely-believed myth that the Chernobyl breach and fire caused thousands, or even hundreds of thousands, of deaths. But the actual, sober, documented death toll of the accident, according to *The Guardian*, a left-wing pro-green usually anti-nuclear publication not likely to be biased toward understating the problem: [\[161\]](#)

Years of subsequent investigation place the death toll of the disaster at approximately 43 people, with deleterious health effects failing to materialise at any appreciable rate. That this information is surprising to many is indicative of quite how polarised the discussion on such a vital topic has been.

It's probably worth pointing out that Chernobyl was not a sanely designed American power reactor, but a Soviet design whose primary purpose was breeding plutonium, hidden behind a facade of power generation. The graphite used as a moderator in such reactors can catch fire, which is what happened there. The water used as a moderator in American power reactors cannot.

One example of how poorly the broad-brush emotional take on such issues serves us is the burgeoning environmental consciousness in the 60s and the ensuing regulation. The Clean Air Act was originally a valuable piece of regulation, saving over 50,000 lives per year in the US by reducing coal-fired air pollution. This was a very good thing—I remember, at age twelve, being the youngest pallbearer for my grandfather, who had died of emphysema. And yet at the same time, the people who rightly wanted to reduce coal pollution were pushed aside. Militant activists completely ignored the actual safety and cleanliness of nuclear power and vigorously propagated the falsehood that nuclear power plants could explode as monstrously huge atom bombs, destroying whole cities with a single accident. They cannot explode. An explosive chain reaction requires an unmoderated critical mass with 80% or more enrichment. Power reactors

use a moderated reaction in uranium only enriched 3%. And yet the Nader groups, among others, actively made the claim that they could explode.

[162] Numerous polls done in the aftermath of the Three Mile Island accident revealed that the activists' misinformation had done its work: some 66% of Americans believed that a power reactor could explode like an atom bomb, vaporizing a city and covering a state with fallout.

Unfortunately the Golden Age science fiction writers had exacerbated the problem, by writing about power reactors back before they had actually been designed: Heinlein's "*Blowups Happen*" and H. Beam Piper's "*Day of the Moron*" feature power plants blowing up, for example. This was amplified in popular entertainments such as James Bond's *Dr. No*. What's worse, the New Age pseudoscience fiction writers of the 70s and 80s claimed power plants could explode even though they knew better. SF author Jerry Pournelle writes:

A science fiction writer friend, a lady I respect, called on me the other day. She wanted a dramatic incident in a story. How, she asked, might a character cause a nuclear explosion—not a large one, just a little one—at the San Onofre nuclear plant?

I told her to have her character carry an atom bomb into the plant. It's the only way I know of. ...

[She] went away disappointed and muttering about how she could fake it, since the public wouldn't know ...

Two-thirds of all the new generating plants started in 1966 were nuclear.

[163] Had the main thrust of the environmental concern acted to enhance rather than stifle the trend, instead of reducing pollution deaths to 10,000 per year by making power more expensive, we could have reduced them (and CO₂ emissions) essentially to zero by 1990 or so, and made energy considerably cheaper instead. Energy poverty is estimated to kill roughly 28,000 people annually in the US from cold alone, a toll that falls almost entirely on the poor. [164] In the intervening 25 years, we could well have saved a million lives.

But instead the scare industry made considerable hay, and no little cash, by conflating nuclear weapons and nuclear power. And then the utilities and the regulators responded to the Three Mile Island accident with one of the

more blatant displays of “shut up and trust us” arrogance on record. This handed the anti-nuclear activists victories they hadn’t deserved on several levels. [\[165\]](#)

We had a confluence of bad design decisions at TMI, some of them made by the U.S. Congress. U.S. law specifically prohibited using computers to directly control nuclear power plants. ... Now nuclear energy can be mighty dangerous and is not something to be messed with lightly, but another irony in this story is that nuclear power is actually pretty simple compared to many other industrial processes. The average chemical plant or oil refinery is vastly more complex than a nuclear power plant. The nuke plant heats water to run a steam turbine while a chemical plant can make thousands of complex products out of dozens of feedstocks. Their process control was totally automated 30 years ago and had an amazing level [of] safety and interlock systems. A lot of effort was put into the management of chemical plant startup, shutdown, and maintenance. The chemical plant control system was designed to force the highest safety. So when manufacturing engineers from chemical plants looked at TMI, they were shocked to see the low-tech manner in which the reactors were controlled and monitored. To the chemical engineers it looked like an accident waiting to happen.

The bottom line is that TMI was caused by political micromismanagement and a complete lack of enlightened control system design in the plant itself. At no time was the public in any danger, but fear among the public was engendered by activist falsehoods exacerbated by dismally incompetent education.

As a result, the full metastasis of reguloma infected the power industry, raising prices to stratospheric heights. The editors of Britain’s online tech webzine *The Register* point out:

Most intermediate level waste is barely radioactive at all. If you put a completely legal luminous watch in a barrel containing half a tonne of dirt, that dirt would technically be intermediate-level nuclear waste according to the regulations. ... Despite the fact that it is not

radiologically dangerous in any realistic way, “intermediate level nuclear waste” must nonetheless be expensively processed, packaged, securely stored and one day eventually disposed of in a special geological vault. It’s projected to make up 99.7 per cent of the UK’s “higher activity” waste in future—that is waste which you aren’t allowed to just chuck into a landfill—and as such it has accounted and will account for the great majority of the cost of nuclear waste management.

Ever wonder why nuclear power never became too cheap to meter?

Early in life I had noticed that no event is ever correctly reported in a newspaper.

—George Orwell

I’ve never been present at an event that the media reported accurately.

—Robert A. Heinlein

Proliferation

A slightly firmer connection to reality is the worry that a fully-developed and widely-deployed nuclear power sector might provide an avenue for rogue states and terrorists to obtain nuclear material for nefarious purposes. As far as getting bomb-grade enriched uranium, this seems unlikely; turning the 3% enriched uranium used in reactors to the 80% enriched used in bombs requires the same machinery and nearly as much processing as refining it from raw natural uranium. An example case in point is Iran’s nuclear project. Similarly, the chemical processing of the highly-radioactive fission products to extract plutonium requires if anything more equipment and expertise (including Waldos!). In either case the resources and effort needed are at a national scale, and every nation with a propensity to try it is being very carefully monitored.

The ubiquitous surveillance Americans are subjected these days to makes it unlikely that any significant effort would be able to proceed long

undetected. It is not uncommon for patients who have had radiomedical thyroid treatments to be pulled over by police using DHS-supplied gamma detectors. Elsewhere, persons willing to try for nuclear weapons, whether bombs or merely nasty dust, do not have to try to raid the garbage cans of American power plants. They are likely to get ample direct support (including all the materials they need) from chess-playing global superpowers; North Korea may have been a case in point.

In any case, a shift from big 1960's-era power plants to more modern design small modular reactors, factory-built, self-contained, and buried in operation, would render them essentially unavailable to bad actors. The stagnation in progress in nuclear technology has made the problem of proliferation worse, not better.

On the other hand, at the current levels of sophistication in molecular genetics, one would be considerably more likely to succeed in a major terrorist action by playing around with the flu virus. It might well be the case that if we allowed a small amount of nuclear material onto the black market, we might distract them into less productive pursuits.

Speed Limit: 1

The Nobel Prize in Medicine in 1946 was won by Hermann J. Muller for the demonstration that ionizing radiation caused genetic mutations, in his particular case using X-rays on fruit flies. In his acceptance speech, he said:

Both earlier and later work by collaborators (Oliver, Hanson, etc.) showed definitely that the frequency of the gene mutations is directly and simply proportional to the dose of irradiation applied, and this despite the wave-length used, whether X- or gamma- or even beta-rays, and despite the timing of the irradiation. These facts have since been established with great exactitude and detail, more especially by Timoféeff and his co-workers. In our more recent work with Raychaudhuri (1939, 1940) these principles have been extended to total doses as low as 400 *r*, and rates as low as 0.01 *r* per minute, with gamma rays. They leave, we believe, no escape from the conclusion that there is no threshold dose, and that the individual mutations result from individual “hits,” producing genetic effects in their immediate neighborhood.

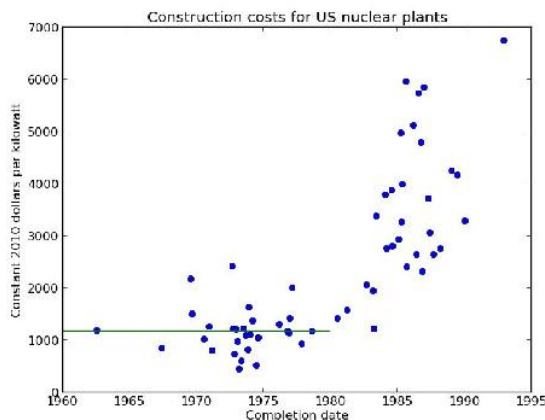
This assertion, oft repeated by Muller and associates, became the basis of what is called the Linear No Threshold hypothesis of radiation damage. It is in fact reasonably well demonstrated that doses *above* 400 rads, an exposure that today would be called 4000 milliGray, [\[166\]](#) have a linear effect. But Muller considerably overstated his case. 4000 mGy is a huge dose; in fact, 50% of humans die from it if received in a short period. A typical CT scan, for comparison, is 10 mGy. The linear no-threshold (“LNT”) hypothesis has never been rigorously tested, and yet it seems to have become received wisdom in the radiophobic culture of the regulators. Today *nobody* believes Muller’s other assertion, that the impact of the dose does not depend on the timing. It’s generally held among radiation health physicists that a “protracted” dose received over the course of a year, for example, is between one half and one tenth the risk factor of an “acute” dose received in an hour or less. [\[167\]](#) You can drink a glass of wine every

day with no problem whatsoever, but I wouldn't recommend drinking 20 gallons in one go.

In fact, a re-examination [\[168\]](#) of the results of the actual data from Muller and his colleagues, notably Curt Stern in the later 40s, indicate that there is a no-harm threshold somewhere below 500 mGy. A wider-ranging survey of the literature suggests that

Among humans, there is no evidence of a carcinogenic effect for acute irradiation at doses less than 100 mSv and for protracted irradiation at doses less than 500 mSv. [\[169\]](#)

Even the pusillanimous NRC admits, [\[170\]](#) and I quote, "But there are no data to establish a firm link between cancer and doses below about 10,000 mrem (100 mSv)." And they then proceed to point out that that level is 100 times greater than they allow for public radiation exposure. This is like setting a speed limit of 1 MPH because people have been injured doing 100. You can imagine what regulations made on the basis of this kind of thinking did to the cost of a nuclear power plant. [\[171\]](#)



Construction costs for nuclear power plants skyrocketed after the establishment of the DOE. Horizontal line is the pre-1980 average, at \$1175/kW. At today's prime rate of 3.25%, that would amortize to about half a cent per kWh. Note that regulation also considerably bloated construction times.

Yes, nuclear today is expensive. Shipping would be expensive too if trucks had to operate with a speed limit of 1 MPH.

A study by economist Peter Lang [\[172\]](#) found that worldwide, the cost of nuclear plants was decreasing by about 25% for each doubling of capacity in the 50s and 60s, and then did a turnaround with the rapid rise we have seen. He calculates that had the earlier trend continued the price of power would have fallen to 10% of what it is, and “the extra nuclear generation could have exceeded the actual generation from coal by year 2000 (assuming electricity demand did not change). If the extra nuclear generated electricity had substituted for coal and gas generation, about 9.5 million deaths and 174 Gt CO₂ may have been avoided.”

Science writer Ronald Bailey on the specifics:

The 1971 D.C. Circuit Court case *Calvert Cliffs* required the United States Atomic Energy Commission (AEC) to comply with a mandate to prepare environmental impact statements for proposed actions. The AEC reacted by suspending all licensing for nuclear power plants for 18 months while it devised new rules. In a 2017 essay, Carnegie Mellon historian Andrew Ramey notes that this was “the opinion which had the most far-reaching and detrimental effect on the development of nuclear power”; it is now regarded as “nuclear opponents’ biggest court victory.” But it wasn’t the only hurdle.

The Energy Reorganization Act of 1974 abolished the AEC, handing its regulatory powers to the Nuclear Regulatory Commission. That entity’s sole focus on safety resulted in lengthening construction times for plants from four to 14 years. Tightening regulations meant orders for new nuclear reactors had slowed to a trickle even before the Three Mile Island meltdown in 1979. Subsequently, plans for nearly 60 more reactors in the U.S. were scrapped.

The Wall Street Journal put it: [\[173\]](#)

The consequences have been incalculable. Not from any intrinsic cost, safety, or efficiency advantage coal became the world’s go-to electricity source in the early 21st century. China and India today

would not be opting for coal. They would be choosing among an array of off-the-shelf, affordable, safe and clean nuclear reactors developed in the advanced industrial countries.

Nuclear power is probably the clearest case where regulation clobbered the learning curve. Innovation is strongly suppressed when you're betting a few billion dollars on your ability to get a license to operate the plant. Besides the obvious cost increases due to direct imposition of rules, there was a major side effect of forcing the size of plants up (fewer licenses); fewer plants were built and fewer ideas tried. That also meant a greater cost for transmission (about half the total, according to my itemized bill), since plants are further from the average customer. Sherrell Greene, a long-time nuclear technologist at Oak Ridge:

The environment in today's nuclear energy enterprise is hostile to innovation. Not by intent, but in reality nevertheless. The industry is highly regulated. It is very costly to do research, development, and demonstration. It's a very capital-intensive business. The barriers to entry are incredibly high. The down-side risks of innovation are more easily rendered in practical terms than the upside gains. Often it seems everyone in the enterprise (federal and private sectors) are so risk-averse that innovation is the last thing on anyone's mind. In this environment, "good-enough" is the enemy of "better". Humans learn by failing. It's the way we learn to walk, talk, and ride a bicycle. Our environment today has little tolerance for failures at any level. There's no room for Thomas Edison's approach to innovation in today's world. On top of all of this, or perhaps because of it, the nuclear industry invests less on R&D, as a percentage of gross revenues, than practically every other major industry you might name. [\[174\]](#)

The startup company NuScale is intent on developing modular reactors, small enough to be built in a factory, and thus cutting costs, construction times, and so forth significantly. NuScale has to date spent \$505 million dollars [\[175\]](#) just to produce the 12,000 pages of paperwork the NRC requires simply for an application. The company estimates that the regulatory process will delay actual production until 2026. Each already-

approved, already built, already licensed, already operating nuclear plant spends an average \$4.2 million per year, purely on regulatory paperwork. A clear case that bureaucracy was the main factor in choking the advance of nuclear power in the US can be found in the one place where it didn't happen, the US Navy. Former Navy Secretary John Lehman writes: [\[176\]](#)

Working with the bipartisan leadership of the Joint Committee on Atomic Energy, the Senate and House Armed Services Committees and the secretary of energy, we constructed ... a position having executive power to prevent meddling from the layers of bureaucracy that were creating chaos in most defense programs. Importantly, we gave the new incumbent complete control of the selection and training of personnel. To ensure that such a powerful executive stayed long enough to execute programs and ensure accountability, a nonrenewable term of eight years was established.

That successful effort was put into an executive order by President Reagan that has worked effectively for 34 years. [The Naval Nuclear Propulsion Program has] been protected from the 970,000 Pentagon bureaucrats whose paralyzing bloat has made a hash of most Army, Navy and Air Force weapon programs. The reason for Navy nuclear success is because there has always been one strong experienced person in charge and accountable, standing like a stone wall against the bureaucratic onslaught.

The Navy has over 6000 reactor-years of accident-free operation. It has built 526 reactor cores (for comparison there are 99 civilian power reactors in the US), with 86 nuclear-powered vessels in current use.

People today know a lot less, and know a lot more that ain't so, about technology in general and nuclear power in particular than they did in 1962. That was of course the premise of Wells' *Time Machine* with its degenerated Eloi. It was echoed in the Golden Age by C. M. Kornbluth's 1951 *The Marching Morons* (whose premise was lifted directly into the movie *Idiocracy*), Piper and McGuire's 1953 *Null-ABC* (about a future in which everyone is illiterate), and most famously Ray Bradbury's 1953 *Fahrenheit 451*. However, most of the mainstream science fiction of the Fifties and Sixties—including *The Jetsons*—assumed that in the future,

people would be better, not worse, educated about science and technology. Elroy takes electronics along with fingerpainting in grammar school. Judy, in high school, takes geopolitics, Esperanto, and “space calculus.” And yet the opposite has happened; we’re in a situation more like Edgar Pangborn’s *Davy*, set in a post-apocalyptic future where the Holy Murcan Church bans “anything that may contain atoms.”

Remember that before the bureaucratic morass, construction of nuclear power was \$1175 / kW. A 2% per year increase, *i.e.* the Henry Adams curve, in the average American’s 10 kW would have required a \$235 investment per capita per year. This would tend to increase with the power total, but to decrease with the learning curve and as a percentage of a robustly growing economy. But in any case we have much more than enough slack to get us back on the Henry Adams Curve, for many years to come.

Did we simply run out of useful, big, important technological innovations ca. 1970? We could have had flying cars in 1940, but for WWII. We could have started on nanotech in 1960. We could have started on solar power satellites in the 70s. The low-hanging fruit of nuclear power was left to rot on the ground and sprayed with the kerosene of hysteria and ignorance.

... And men with hoses squirt kerosene on the oranges, and they are angry at the crime, angry at the people who have come to take the fruit. A million people hungry, needing the fruit—and kerosene sprayed over the golden mountains.

And the smell of rot fills the country. ...

There is a crime here that goes beyond denunciation. There is a sorrow here that weeping cannot symbolize. There is a failure here that topples all our success. The fertile earth, the straight tree rows, the sturdy trunks, and the ripe fruit. And children dying of pellagra must die because a profit cannot be taken from an orange. And coroners must fill in the certificate—died of malnutrition—because the food must rot, must be forced to rot.

—Steinbeck, *The Grapes of Wrath*

Shortfall

Culture evolves as the amount of energy harnessed per capita per year is increased, or as the efficiency of the instrumental means of putting the energy to work is increased.

—Leslie White

Choking progress in one field of energy, nuclear being the key case in point, has raised the price of other forms of energy and ultimately of everything. Manufacturing costs have risen, and obviously the same thing has happened to transportation. Where costs haven't actually gone up, they haven't gone down as fast as they would have under the historic trend. A huge amount of effort, from engineers to construction workers, has been misplaced to make things more efficient at energy use than they would otherwise need to be. The Climate Change Business Journal lists nine segments of the climate-change related industry: [\[177\]](#) renewable energy, carbon capture and storage, energy storage, energy efficiency, green buildings, transportation, carbon markets, adaptation, and consulting and research. They estimate the total business as grossing about one and a half trillion dollars a year. To provide some perspective on how much money, resources, effort, and so forth that represents, it is about the same as the sum total of all the military budgets of all the world's nations. According to the IEA, \$125 billion is spent on solar and wind subsidies alone. Some of the approximately 50 subcategories of the climate-change industry are useful regardless of the climate change scare (indeed one of them is nuclear power); but we can estimate that a good trillion dollars a year is being simply thrown away. [\[178\]](#) That's a worldwide number, but for comparison it's roughly 6% of the US GDP, or about as much as we spend on conventional energy. Imagine that that money, effort, talent, and resources had been put to work doing something useful.

In the 1970s, when the Department of Energy was created and energy per capita flatlined, one used to hear a lot of well-meaning people decry the space program and say how we should pay attention instead to the problems we had right here on earth. But most of the problems we have here, have to do with poverty. Poverty is ameliorated by cheap energy. Bill Gates, nowadays perhaps the world's leading philanthropist, puts it, "If you could

pick just one thing to lower the price of—to reduce poverty—by far you would pick energy.”

In his book of futurism *2081*, Gerard O’Neill, the conceptual inventor and a prime advocate of space colonies and solar power satellites, wrote:

A great deal of misinformation is in circulation in regard to the energy situation on Planet Earth. Some writers have argued, for example, that worldwide living standards could be brought up to decent human minimums without a corresponding increase in energy usage. That just isn’t so. Power consumption and standard of living go hand in hand. ... For every watt of power a citizen uses, his nation produces a dollar a year in goods and services.

A survey and analysis of more recent economics publications tends to confirm the relationship. [\[179\]](#) “Energy consumption Granger-causes real GDP per capita and vice versa in the long run, which implies that an increase in energy consumption leads to an increase in economic growth and vice versa.”

Counting watts is a better way to measure a people’s standard of living than counting dollars. We do have an economy now that produces twice as many dollars of apparent economic activity per watt of energy consumption than in 1970. But those who claim that is a good thing are missing the point. We have made energy itself more expensive; dollars per kWh generated in the US has increased by 300% while actual power generated has increased by only 26% [\[180\]](#) (more dollars, less value); we have forced everyone to pay more for energy-efficient cars, houses and appliances (more dollars, less value); we blow hundreds of billions on worthless public transit (more dollars, less value). Yes, we’re spending more dollars but (outside of computing and communication) most of what we’re getting for them is virtue signaling. Counting watts, I repeat, is a better way to measure a people’s true standard of living than counting dollars. The Great Stagnation and the Henry Adams flatline were not merely coincidental; they were synonymous.

As Clarke put it,

In this inconceivably enormous universe, we can never run out of energy or matter. But we can all too easily run out of brains. ... If, as is perfectly possible, we are short of energy two generations from now, it will be through our own incompetence. We will be like Stone Age men freezing to death on top of a coal bed.

The Great Physics Stagnation

Understanding the low-energy fission process has proved so difficult that, even 60 years after the Bohr-Wheeler liquid-drop statistical model, which provided a qualitative understanding of fission, there does not seem to exist a well-defined and universally accepted theory.

—A. J. Cole, *Statistical Models for Nuclear Decay* (2000)

*Today, education concerning nuclear physics is in an appalling state. On the one hand, discussion of the politics of nuclear issues is to be heard almost daily on the evening news. On the other hand, a visit to any typical bookstore in the US will reveal a total lack of interest in the academic field of nuclear physics. Of course, popular renditions of the “quantum revolution” circa 1920 continue to be written, but even university bookstores rarely have any texts on the nucleus itself. And if you find a book on nuclear physics, check the copyright date! Books written in the 1950s or 1960s and reprinted **in unaltered form** are on offer to students in the twenty-first century.*

—Norman Cook, *Models of the Atomic Nucleus* (2010)

Atomic nuclei shape the nature of our reality: around 99.9% of the mass of all matter is contained within them. Yet in spite of their ubiquity and significance, they still remain relatively poorly understood by contemporary physics.

—Univ. of Warsaw Faculty of Physics (2015)

Arguably the most important physical phenomenon discovered in the 20th century was nuclear fission. That was certainly the consensus of mid-century science-fiction writers: several of them, ranging from H. Beam Piper to Larry Niven, dated their future histories from the first sustained chain reaction (or in some cases, bomb). Referring to today’s year as 76 AE (Atomic Era) instead of 2018 AD (or CE) is a subtle way of making the

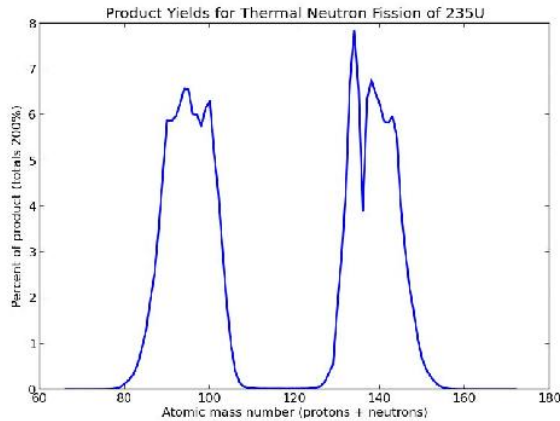
reader feel part of a distinct new phase of history. It's certainly clear that SF writers of the 50s and 60s believed that we were in such a new technological order of things. Outside of science fiction, the existence of nuclear weapons reshaped the dynamics of world politics in ways we are still grappling with.

So you would imagine that fission would be one of the most studied, and by now best understood, of processes. After all, physics had advanced well beyond it: we have generally accepted theories of quantum electrodynamics (QED) and quantum chromodynamics, which explain the outer atom and the insides of nucleons, respectively. We have very high-energy particle accelerators which continue, so far, to confirm the "Standard Model" of very deep physics.

But quite surprisingly, there is still no generally accepted theory that gives a good account of nuclear fission. From the introduction of Krane's classic introductory text: [\[181\]](#)

Nuclear Physics lacks a coherent theoretical foundation that would permit us to analyze and interpret all phenomena in a fundamental way; atomic physics has such a formulation in quantum electrodynamics, which permits calculations of some observable quantities to more than six significant figures. As a result, we must discuss nuclear physics in a phenomenological way, using a different formulation to describe each different type of phenomenon, such as α decay, β decay, direct reactions, or fission.

Two of the leading theories, the liquid drop model and the nuclear shell model, each have areas where they give good predictions in agreement with experiment. The shell model, for example, which is similar in concept to the electron shell model of the outer atom, gives good accounts of the experimentally observed spins, parities, excited energy levels, and similar properties of nuclei, and their periodic properties as a function of nucleon numbers. The drop model does a good job predicting the observed size of a nucleus, and the energy produced by a fission event given the sizes of the resulting fragments. Unfortunately, it also predicts that fission is most likely to split a nucleus in half, i.e. into two equal fragments; but that is not what happens.



Fission yields: nuclear fission almost always results in fragments of unequal size. (England & Rider, LANL)

Neither does the nucleus shatter into a random scattering of fragments, as if it were a solid object being hit by a hammer (or a liquid drop being splattered). It divides almost always into just two pieces, in a very constrained and characteristic set of unequal sizes. [\[182\]](#) [\[183\]](#) (It may be that quantum chromodynamics forms an adequate theory, but if so it is in the same way that quantum electrodynamics is an adequate theory of the weather. In 2016, an international team did a very nice simulation of part of the Pu240 fission process, solving about 56,000 complex, coupled, nonlinear, time-dependent, three-dimensional partial differential equations using nearly 2,000 NVIDIA GPUs on the Titan supercomputer at ORNL. Their paper begins, [\[184\]](#) “Nuclear fission has almost reached the venerable age of 80 years and it still lacks an understanding in terms of a fully quantum microscopic approach,” and later “The nature of the dynamics of a fissioning nucleus appears quite surprising...”) The heyday of nuclear physics was a full century ago. In 1911, Ernest Rutherford, with his assistants Geiger and Marsden, did an experiment in which they bombarded an extremely thin gold foil with alpha particles. Rutherford himself described the results: “It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.” What had happened was that a very few—one in 20,000—of the alpha particles bounced back. Almost all of them went straight through the foil

with a deflection of about one degree. Rutherford hypothesized that there was a dense nucleus in the atom that concentrated essentially all the mass and all the positive charge. (The word “nucleus” had been used for the central organelle in a cell since 1831, and found a very straightforward metaphorical extension. The word “fission” was also borrowed from cellular biology.) But the results of the experiment—and the existence of the nucleus—were completely unpredictable by any physics known at the time.

Similarly, throughout the 1930s, scientists did a series of experiments bombarding various elements with the newly discovered neutron. Although Fermi first tried uranium in 1934, it wasn't until 1938 that Hahn proved fission was occurring by identifying barium (atomic mass number 138 in the chart above) among the products. And again, this was first shown experimentally, and the theory revamped afterwards to take account of it. Then in 1939, things started heating up. In Europe, WWII formally got underway, and many of the best physicists fled to the United States. Leo Szilard, who had been the leading proponent of the idea of a neutron-mediated chain reaction, prevailed on Einstein to write the now-famous letter to Roosevelt which would ultimately lead to the Manhattan Project. A fission chain reaction needs not only an isotope which fissions when struck by a neutron, releasing energy, but one which produces more neutrons in the process. In 1940 there was good evidence that U235 might be usable. U235 is however a minor constituent, only 0.72%, of natural uranium; the remainder, U238, is for practical purposes not fissionable. Furthermore, it is extremely difficult to separate isotopes, since they are essentially identical chemically. By 1941, however, McMillan and Seaborg had discovered that a new element could be produced by bombarding U238 with neutrons, and that it was even more fissionable than U235. In 1942, Seaborg produced a visible piece of the new element, which he named Plutonium. Often overshadowed in the histories by Fermi's operation of a sustained chain reaction using uranium in the same year (“the Italian navigator ...”), this was still a remarkable historic event for a host of reasons. It was not only the first plutonium, but the first visible object composed of any manmade element. Indeed, the first full-sized uranium reactors, built at Hanford, Washington as part of the Manhattan Project, were built not to produce power but plutonium.



Hanford B, the first full-sized reactor, built in 11 months during WWII to produce plutonium. (author)

Physics Stagnation, Redux

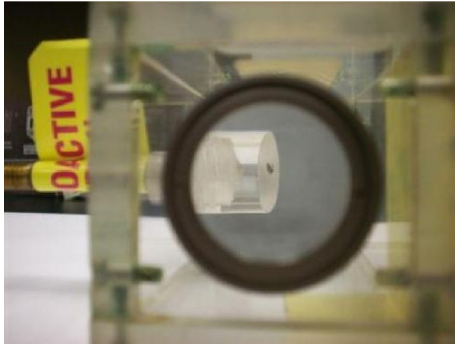
And some things that should not have been forgotten were lost. History became legend. Legend became myth.

—J. R. R. Tolkien

Recently, I had the opportunity to test out Prof. Cook's thesis, quoted above, about the current state of nuclear physics literature. One of the lamentable aspects of 21st century technology is the death of the used bookstore; it had always been a particular pleasure to visit one and spend a couple of interesting hours perusing their stacks when in an unfamiliar city; but the business has largely died. On this occasion, however, I happened to be in Redmond, Washington, home to Microsoft and thus a population of technically interested people (*i.e.* nerds). A good used bookstore remained in business. Given its clientele, it had a substantial and well-appointed science section.

I visited the store with the expressed intent to buy every single book they had on the subject of nuclear physics. This proved distressingly easy. I left carrying three books in one hand, the most recent an overview by Isaac Asimov that was 25 years old.

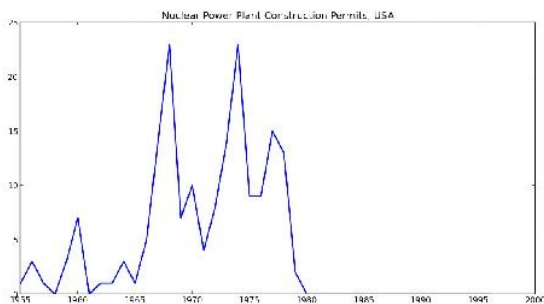
In 2008, physicist Phil Broughton of U. C. Berkeley had been called to examine a bucket full of old slightly radioactive junk, mostly exhibits from the old display in the Hall of Science there. They were all slated for disposal in a "hot" landfill in Nevada.



Seaborg's speck of plutonium, the first object produced by nuclear transmutation. (Eric Norman)

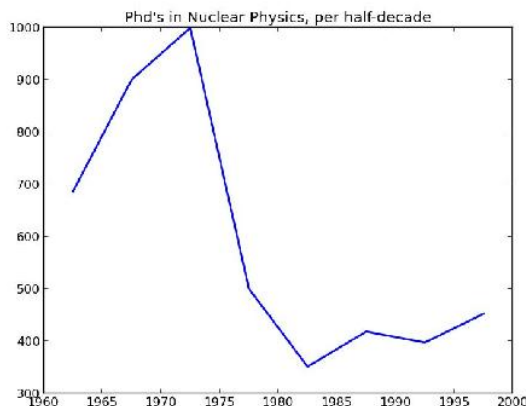
One of the items was a lucite box with stickers dating back to WWII days. The label indicated that it contained “first sample of Pu” weighing 2.7 micrograms. It was Seaborg’s speck: [\[185\]](#) an object of enormous significance, both scientific and historical.

And yet it had lain forgotten for years, and had very nearly been thrown out with the trash. It’s as if someone had found the Declaration of Independence in a National Archives garbage can. The really crazy footnote is that now that it has been remembered and rescued, Berkeley is on the hook for bales of paperwork for licensing and documentation from the NRC. It’s illegal to possess even 2.7 micrograms of plutonium in the US otherwise. And yet notwithstanding its importance and all the documentation it should have had all along, it had been completely forgotten.



Nuclear power plant construction permits in the US crashed at just about the same time private airplane sales did. (EIA)

The suppression of the nuclear industry by the Department of Energy [\[186\]](#) in the US had a number of far-reaching effects well beyond contributing to the Great Stagnation energy flatline. Suppose you were going into science or engineering in the 1980s: would you have picked nuclear physics or nuclear engineering as a promising career choice? Of course not. The number of PhDs in nuclear physics over the period reflects this clearly:



US PhDs in nuclear physics (NSF)

The bottom line is that interest, and career prospects, in nuclear physics imploded in the Seventies; the field languished and major discoveries stopped coming. Most reactors still operating today are mid-Sixties “Generation II” pressurized water designs. [\[187\]](#) For comparison, the most popular computer of similar vintage was the IBM 1401, coincidentally considered second generation in its own line, which as we have seen filled a room, rented for \$20,000 per month (today’s dollars), and came with up to what we would today call 0.000016 GB of hand-threaded ferrite-core memory. [\[188\]](#)

Not only were there fewer nuclear physicists in the '70s and '80s, but the character of a shrinking field becomes markedly different from that of an expanding one. Politics increases; orthodoxy reigns; new ideas are viewed with suspicion and hostility. Paradigm shifts become almost impossible.

——AAUGHH!!——

The prospect of cheap fusion energy is the worst thing that could happen to the planet.

—Jeremy Rifkin

Giving society cheap, abundant energy would be the equivalent of giving an idiot child a machine gun.

—Paul Ehrlich

It would be little short of disastrous for us to discover a source of clean, cheap, abundant energy, because of what we might do with it.

—Amory Lovins

This sacred autumnal drama, repeated nearly every September or October for over 50 years, has become our collectively-acknowledged paradigm for the uneasy tension between trust and betrayal, hope and despair. To a kid, of course, it was the moment of failure that mattered—not the metaphor. No single act better encapsulated a child's feeling of powerlessness, and I felt Charlie Brown's frustration and disappointment with every bone in my body.

—Eric Schulmiller

Schulmiller is of course referring to the classic setup in the Peanuts comic strip in which Lucy offers to hold the football for Charlie Brown and then yanks it away at the last moment, causing Charlie Brown to lose his footing and fly through the air with a cry of anguish and despair. But in spite of repeated betrayals, Charlie Brown was back at it again every year, gamely trying for the football.

For decades, Green activists have been attacking our sources of energy. Every single one has been demonized. Coal, which liberated mankind from

the Malthusian trap, gave us manufacturing, railroads, and steamships, more than doubled our life expectancy, and saved almost all of us from having to be dirt farmers. Oil, which substantially replaced coal in the twentieth century, made airplanes and the private automobile possible along with the rest of the modern world. Hydropower, nuclear fission, even natural gas have come under the gun of the activists.

The currently fashionable “renewables,” such as wind or solar power, have largely escaped the attacks. Battery-powered electric cars are the darlings of the greens. But this is because they are simply not capable of providing anywhere near the energy or range that civilization depends on at a price it can afford. Should any of these, or other new forms of energy, prove actually usable on a large scale, they would be attacked just as viciously as fracking for natural gas, which would cut CO₂ emissions in half, and nuclear power, which would eliminate them entirely, have been.

Technologists by and large do not understand this. We have for fifty years played Charlie Brown, cluelessly running to provide new, better forms of power in the vain hopes of social acceptability. But the football is always yanked away, the new energy is always demonized, and it never penetrated our thick heads that we are playing a mug’s game.

Fusion was always going to be the new, clean energy source of the future. As long as it was always 20 years away, nobody minded. But in the early days of the cold fusion phenomenon, it suddenly looked as if the millenium might be at hand, and many of the activists let the mask drop with comments like those above. It really has nothing to do with pollution, or radiation, or risk, or global warming. It has always been about keeping energy out of the hands of ordinary people, and it always will be. To a Green, cheap, clean, abundant energy really would be a disaster, because people would gain the ability to change the Earth for the better.

The Baptists are of course the Greens; the bootleggers, not too surprisingly if you think about it, are not only the trillion-dollar “sustainable energy” industry, but the trillion-dollar fossil fuel industry. Put them all in the same boat, and you have a special interest of Titanic proportions.

The classic case, of course, was fission power reactors, the cleanest, safest form of energy ever deployed on a major scale. As a science fiction and technology fan, for most of my life I had been squarely in the “just you wait until we get fusion” camp. Then I was forced to compare the expected

advantages fusion would bring to the ones we already had with fission. Fuel costs are already negligible. The process is already clean, with no emissions. Even though the national waste repository at Yucca Mountain has been blocked by activists since it was designated in 1987 and never opened, fission produces so little waste that all our power plants have operated the entire period by basically sweeping it into the back closet. When we compare the excuses that are advanced to suppress fission with its actual record in use, I can assure you that if fusion, cold or hot, ever succeeds, the same excuses, turbocharged and on steroids, will be trotted out against it. In fact, the one significant advantage that fusion might have had was that there was no obvious critical mass for a chain reaction, and thus reactors smaller, cheaper, and so forth than fission ones might be possible. But the leading fusion project now, the ITER tokamak, is a machine three times the weight of the Eiffel Tower in a supporting structure the size of the Empire State Building. You will not be using this to power your flying car.

If you are a technologist working on some new, clean, abundant form of energy, I wish you all the luck in the world. But you must not labor under the illusion that should you succeed, your efforts will be justly rewarded by the gratitude of the people you have lifted from poverty and enabled to have a bright and growing future. You will be attacked, your work will be lied about by activists, demonized by ignorant journalists, and strangled by regulation.

But only if it works.

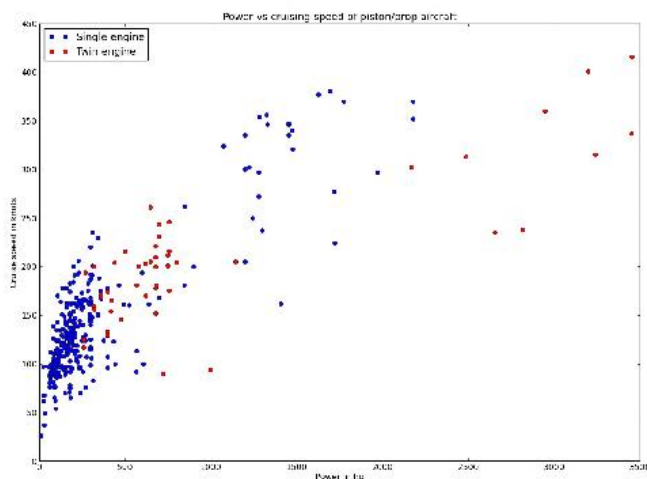
How can we do that when your science and inventions are perpetually changing life for us—when you are everlastingly rebuilding and contriving strange things about us? When you make what we think great, seem small. When you make what we think strong, seem feeble. We don't want you in the same world with us. We don't want this expedition. We don't want mankind to go out to the moon and the planets. We shall hate you more if you succeed than if you fail.

—H. G. Wells, *Things to Come*

13 The Jet Age

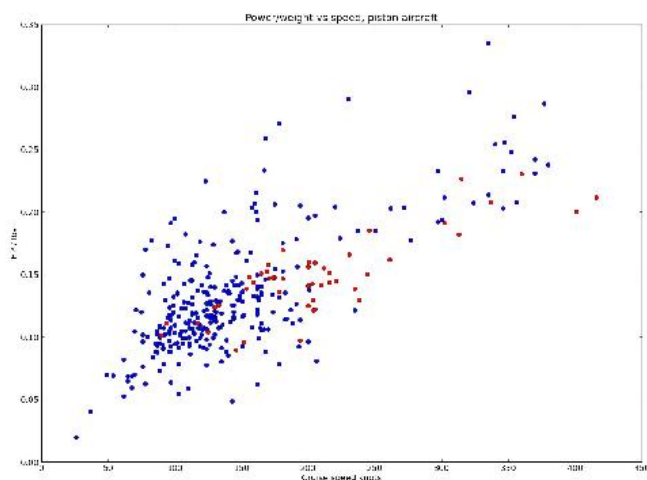
Even considering the improvements possible ... the gas turbine could hardly be considered a feasible application to airplanes mainly because of the difficulty with the stringent weight requirements.
—the Gas Turbine Committee of the U. S. National Academy of Sciences (1940)

Travel theory tells us that if we can make a flying car that only has five minutes of overhead and can do 250 knots once in the air, it would be worth about 5 times as much as a ground car. (250 knots is a speed limit in US airspace below 10,000 feet, so we will use it as a point of departure for speculation. You can't fly much over 10,000 feet without needing oxygen or pressurization.) What are the chances of building such a thing? How much power do we need, for example, to get 250 knots out of our flying car? Here's a graph of a wide range of 20th-century propeller aircraft, showing power vs speed. There's a huge variation in speed at any given power (and vice versa), but it seems possible to design one that gets 250 kts if you have more than 500 HP available:



This graph has an odd structure, apparently; there are two separate bands for single-engine planes, which are interleaved with two bands of twins. What's happening is that the high-power, fast singles are WWII fighters and

the like, built with very different design goals from the small light private planes which make up most of the low end. The variation in power has a lot to do with aircraft weight, of course. Using the same engine, you would get much more speed in a single-seater with barely room for your flight bag than you would in a car-like plane that carries a family of four and their luggage. We can finesse the issue by dividing by the weight of the loaded aircraft. Here are power-to-weight ratios by airspeed:



You can see that the designs are much better mixed, all falling along the same “main sequence”.

A speed of 250 kts means that we need a horsepower number somewhere between 0.15 and 0.25 times the weight in pounds. You can see that the graph curves toward higher speeds at the same power loading over about 150 knots. This is due to the fact you use less and less power to produce a pound of lift the faster you go, so faster airplanes tend to be bigger and heavier. Let’s estimate that with high-tech materials we can make the vehicle 2000 pounds and have it carry 1000 pounds of payload. That means we need somewhere on the order of 600 horsepower. And that’s a problem: a piston engine producing 600 horsepower weighs on the order of 900 pounds. Airplanes with those statistics were produced, in the Thirties and Forties, but they were fighters and racers, more than half engine. We would be much better off with a turbine. The Lycoming/Honeywell LTS101-650C, for example, packs 675 HP in only 241 pounds.

This makes a huge difference. There's a good reason that "Jet Age" vied with "Space Age" as a description of the dawning era in the Fifties and Sixties. The turbine, at least as much as any other new technology, was iconic of the future; they were after all the "Jetsons" in their jet-powered car, and not the "Spacefields" or even the "Atoms Family." And in fact, over the succeeding half-century, turbines have completely changed the technological landscape, especially in air travel, where their very high power-to-weight ratio is of most value. Another fact about turbines that is critical but less commonly appreciated is that they are significantly more reliable than piston engines. A piston aero engine typically must be overhauled every 2000 hours, a small turbine at up to 10,000. At 250 knots, your turbine will take you the better part of 3 million miles. Commercial air travel as we know it today would be impossible without turbines.

Turbines have quite a few advantages as aero engines:

- The leading advantage is power to weight ratio, of course. In the power range of interest, a piston engine might well be 5 times as heavy as the equivalent turbine.
- Turbines can be made to burn a wider range of fuels, burning, as one quip has it, "Anything up to and including fancy French perfume."
- They are nearly vibration-free compared to pistons. This reduces the need for shock mounting and removes a major source of wear and tear on the airframe. (They do produce ultrasonic vibrations that the engineer needs to take into account.)
- Turbines can easily produce copious quantities of compressed air for aerodynamic uses such as blown flaps.
- They can be quite fuel-efficient. Currently, the most efficient form of power generation is combined-cycle natural gas turbines, for example. Jets got a reputation for inefficiency but that was primarily due to using the jet exhaust directly for propulsion. Modern fanjets burn a lot of fuel, but that is because they are producing an enormous amount of power.
- They are more reliable and last longer. The Pratt and Whitney PT6A-67B, an industry workhorse, has a record of one failure per million hours of operation — 11,574 times around the equator at 250 knots. I can live with that.

As an amusing aside, Chrysler built a turbine-powered car in the 60s, more as a concept car than to sell (it would have been way too expensive in those days). But as one of the demonstrations, they gave the President of Mexico a ride in one burning tequila as its fuel.

Turbines are pricey today, but not out of reach given the assumptions of this chapter. If the push to flying cars had been stronger, there would be much more mass production of them, lowering the price, and we would be further down the learning curve in the technology. The learning curve as a rule of thumb says that cost declines as the inverse logarithm of units shipped.

Even without assuming away the Great Stagnation, we might imagine that a turbine-powered flying car would cost the same as a house. Since about 5% of American families have second homes today, there could be plenty of turbines out there, if we had but wanted them. If we had somehow managed to avoid stagnation, and incomes were 3 times higher than they actually are, flying cars might have reached the levels of adoption that ground cars had in 1920.

The bottom line is straightforward: futurists in the Fifties and Sixties making technologically literate predictions of flying cars assumed they would use turbines. A turbine would give your flying car the power to take off vertically and land on a dime like a helicopter, or fly at 400 knots as small bizjets do today. The interesting question is: could it do both?

VTOL

Fort Worth-based Bell Helicopter is dropping the word “helicopter” from its name and is rebranding itself “a tech company redefining flight.”

—NBC 5 Dallas-Fort Worth, Feb 23, 2018

Tilt fans

The VZ-2 tilt-wing was essentially a complete success as a research experimental vehicle, and was the forerunner of the V-22 Osprey in service today.

The Osprey itself must be considered something of a technological success story. Like many military development projects, the program tried to combine too many brand-new technologies in one platform, and it suffered a number of early crashes as a result. One example that will give you a sense of the experimental nature of the early V-22 is that in 1986-1989, when the first V-22s were being built, standard hydraulics in aircraft were 3000 PSI. The Osprey pioneered the use of 5000 PSI hydraulics, including among other things thin-walled titanium hydraulic lines. [\[189\]](#) In the intervening quarter-century, however, the kinks have been mostly worked out. There are 213 V-22s in service currently, and DoD has just (2013) ordered 99 more for about \$65 million each (which includes a quantity discount).



A successor to the V-22 is being tested as I write; the Bell V-280 Valor is apparently leaner and lighter with several design improvements. At least for the military, the tilt-rotor appears to have reached a stage of technological maturity. It seems likely to be the successor to the helicopter where higher speeds are required.

Tilt ducts

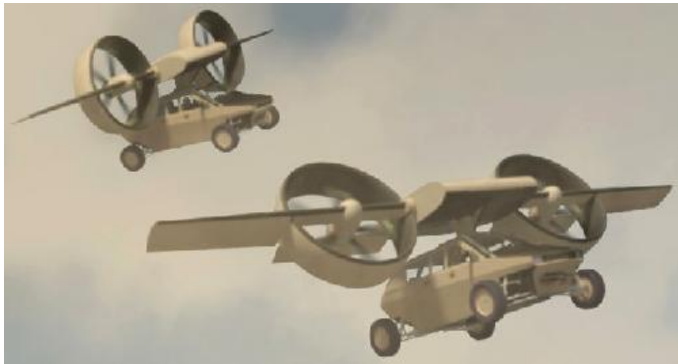


Moller Skycar 400

The best-known attempt to reduce the idea of the X-22A with its 4 tilting ducted fans to practice in a car size is the Moller Skycar. Once in the air the fans tilt to become propulsion, while lift at cruising speed is provided by wings that can be much smaller than the ones that would be needed to support the vehicle at slow takeoff and landing speeds. According to Moller, the design would have a cruising speed of 300 mph and could operate from a 35-foot helipad. [\[190\]](#) The main problem with the Skycar as your flying car is that it remains under development and you can't buy one.

Moller spent decades flying into the headwinds of the regulatory morass, and deserves some credit as an enabling pioneer. He is responsible for the FAA having a "powered lift normal" category for aircraft, for example. To some extent, starting so early turns out to have been a hindrance rather than advantage, however. Moller spent years developing a compact, lightweight, powerful Wankel engine for use in the Skycar; thirty years ago, it would

have been impossible to know that advances in electronics and rare-earth magnets would make a turbine-electric system a better bet.



The military continues to have a perceived need for flying jeeps, and there is a current program with the explicit goal of producing one. The specs in the program documents call for what is essentially a convertible VTOL. The design of the current prototype does have a distinctly 21st-century aspect, though. Like the ConvAirCar, the jeep part detaches to drive off as a jeep. But the top airplane part doesn't just sit there: it's a VTOL autonomous drone, and it flies off by itself to the next jeep or shipping container needing to be taken somewhere. The TX program has moved forward into a development phase, now called ARES, a joint project of the famous Skunk Works and Piasecki Aircraft. You can bet it uses turbines.

The VTOL Dilemma

Given the technical success of ducted-fan VTOLs such as the VZ-4 and X22-A, why didn't they catch on as flying cars? Or at least if they were too expensive for private vehicles, why didn't they get used by the Army and Navy, who after all had enough of a perceived need that they sponsored the research?

To some extent the answer is that ultimately they did. The military, notably the Marines, flew the Harrier VTOL and now flies the V-22 Osprey, a VTOL flying bus that fulfills the roles the X22-A was envisioned for. The F35B Joint Strike Fighter is STOVL, capable of taking off from, and landing on, ships much smaller than a full-sized aircraft carrier. The Marines and the Army may be in the market for whatever the DARPA ARES design ends up as—something much closer to a true flying car, if still twice as heavy due to the armor and other mission requirements. But there is always a tradeoff. The vast majority of aircraft that are fast are not VTOL, and ones that are VTOL are not fast.

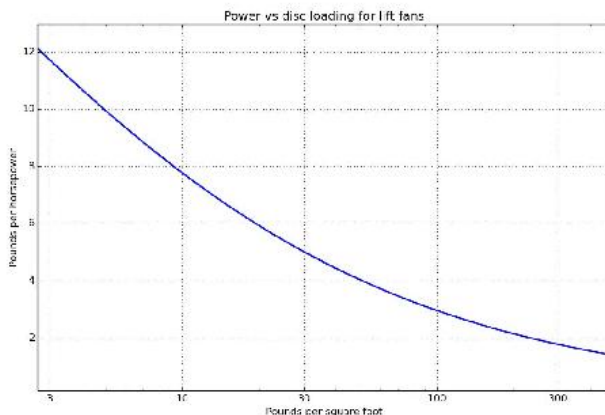
One reason is power. The Doak VZ-4 used an 840-horsepower turbine engine, later upgraded to a 1000-horsepower model. On the chart above, with a power to weight of about 0.3, it should have been able to do about 400 mph; in practice its top speed was 230. The X22-A used *four* turbines at 1267 hp apiece. The Moller, in its current prototype, has eight specially-designed rotary engines that total 700 hp. The Urban Aeronautics AirMule, a modern reincarnation of the VZ-8 AirGeep, uses the 940 horsepower Turbomeca Ariel 2 turbine.



The Urban Aeronautics AirMule (Wikimedia / Timur Saban (CC))

The original Airgeep itself offers an instructive comparison: with its 800 horsepower in twin turbines, it worked quite nicely, even exceeding its designers expectations. A vehicle of similar design, but using considerably less powerful piston engines, was the Curtis-Wright Bee, which never got more than a few inches off the ground.

Turbines use a lot of fuel, but only because they're producing a lot of power. A piston-engined plane at 100 knots might use 10 gallons per hour (mine does), where the recently-certified Cirrus Vision "personal jet" flies at 300 knots using about 150 gph. But the power requirements go up as the cube of the speed; everything else being equal, you'd expect to use 27 times as much fuel (per hour) to go 3 times as fast. (By the way, all else is not actually equal, and there is a big efficiency premium for a big jet. Modern airliners get something like 80 passenger miles per gallon.) If you're going to put that much engine in your VTOL flying machine, you're buying a private jet—but one that can only go half as fast as a private jet. If you look at the power/weight graph again, you'll see that a car-sized craft with 1000 horsepower should be able to do airliner speeds, e.g. 450 knots. If instead you go slow and use the power to hold yourself up, fuel per mile goes up alarmingly. At the extreme, stationary hovering, fuel per mile is infinite! Alternatively, you could put the same 1000-hp turbine in a helicopter (e.g. the Bell UH-1 "Huey") and carry 4 times the payload—but only cruise at 110 knots. So there really is a design dilemma: other things being equal, being VTOL costs you half your speed as a flying machine.



Power vs thruster area loading for static thrust fans at sea level. [\[191\]](#).

Here's the relationship of power required for a given lift fan (or set of fans with a given total area). The horizontal scale is the ratio of weight to thruster area, and the vertical tells you how much lift you get per horsepower of motor.

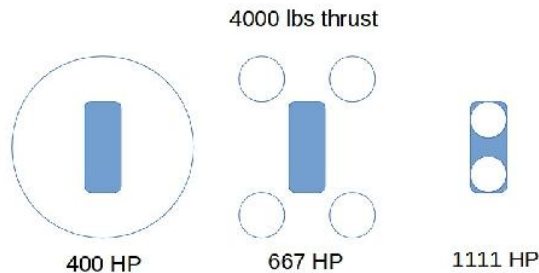
Suppose, for example, that you want to build a VTOL flying car by having four 10-foot propellers that folded up like skis on a roof-rack and deployed into a standard quadcopter arrangement around the car. They would have a total disc area of 314 square feet. The total weight of your car is 3000 pounds, and the rule of thumb is you need twice the weight of the vehicle in thrust for safe takeoffs and decelerating to a landing. That gives you a disc loading of about 19 pounds per square foot. The graph tells you that you can lift 6 pounds per horsepower, so you need 1000 horses.

In practice helicopters use more thruster area and don't get designed to quadcopter peak power guidelines. The R44 only lifts 2.5 pounds per square foot of disc area. It manages to get by with 250 HP takeoff power, but climbs out sedately at a low angle. Our quadcopter car, like a real quadcopter, could take off straight up at one G acceleration and climb like a homesick angel.

Parenthetically, the reasons for the design tradeoffs have mostly to do with the difference between the mechanically driven rotor and electrically powered props. The rotor is big and heavy, and acts as an energy store. You spool that up before takeoff and draw on it using the collective pitch control. The quadrotor's props have no collective, and must be light for control responsiveness; it has no energy store equivalent to the rotor. Thus it needs to have the extra power available in the motors. The extra power headroom is also valuable since unlike the helicopter, the quadcopter uses rapid differential power variations for attitude control.

In any case, the tradeoff is clear. If you want to lift a lot of weight, for a given power expenditure, you must be blowing a lot of air down slowly. To go fast, you have to squeeze that power into a smaller, faster, jet—and get less force out of it. Helicopters live on the left end of the graph with few pounds per square foot of their many hundreds of square feet disc areas; rockets are out past the right end with tons per square foot of nozzle. The VTOL ducted fan craft such as the Doak VZ-4 are in the middle—a compromise that is suboptimal for either of the desired flight regimes. The

Doak in practice used about 800 HP to lift or hover, but only 200 in straight and level flight.



Helicopter, quadcopter, and VTOL arrangements of thrust fans shown against the footprint of a Camry.

The hard part of flying is takeoff and landing, where the lower speeds mean that the lift of the wings is considerably less—lift is proportional to the square of the speed. This is frustratingly backwards for the flying car designer. At speed and at altitude, it doesn't matter what wings, fans, and other protuberances there are; there's plenty of room for them. But you don't need them, because there could be enough lift from the body alone. On the ground, at takeoff, clearing trees, buildings, traffic, and so forth, wings and rotors are much more of a bother and a hazard, but you need them the most.

There are three major ways that have been tried to solve this dilemma. The first is simply to pour on the power and use jets, inefficient as they are at low speeds, for lift. Fighter jets typically have more thrust than weight, anyway. The Harrier is the classic example of this approach. Its engine produces 23,800 pounds of thrust. With a specific fuel consumption of 0.76, it burns 300 pounds of jet fuel *per minute* in hover.

The second approach is to use some compromise prop-rotor or tilting ducted fan for both takeoff and cruise thrust. Efficiency can be enhanced in both modes by use of variable-pitch propeller blades. These are standard on high-end prop planes anyway, and are nothing exotic.

What *would* be exotic would be extensible blades. Propeller blades that could double in length would make the fan disc vary in area by a factor of

four, very likely enough to solve the dilemma. The problem is that centrifugal force on the blades can be in the range of ten thousand gravities, which makes it hard to engineer a reliable retracting mechanism.

The third approach is to use separate lift-off and cruise fans. The main difficulty is that the lift-off fans are going to be big, unwieldy, high-drag protuberances. You're either left having to overcome their drag or retract them somehow, a non-trivial engineering challenge.

Fan-in-wing

There is one place you can hide the lift fans while in forward flight: inside the wings. An experimental design of this form, the Ryan XV-5, was tried in the mid-Sixties. It was supported in vertical takeoff and landing by a downward-blowing fan in each wing and one in the nose. These were covered by lids to form a smooth wing surface while in forward flight. The XV-5s worked, although both of the prototypes crashed at one time or another killing their test pilots (once by ingesting into the fans a dummy on a sling that was being used to test rescue capabilities).



The Ryan XV-5B, in NASA livery.

Rather than run a driveshaft to the wing fans, the fans were driven by an integrated turbine pushed by diverted jet blast. The fan thus driven had a static thrust about three times that of the original jet. A design flaw was that there was no intermediate mode between fan lift and forward flight: you flipped from fans to jets with a sickening lurch. This seems like something

that more experience and subsequent generations of design could almost certainly have ameliorated, however.

The XV-5 was built to the scale of a fighter jet: it had a max loaded weight of 13,000 pounds, and boasted two turbojets with 2600 pounds of thrust each. Furthermore, it had performance in the range of a commercial jet: a max speed of 475 knots (about 550 mph) and service ceiling of 40,000 feet. Its drawbacks were mostly that it was slower than conventional fighter jets, and didn't have room for weapons; the lift system consumed all the internal space.

It would have made one hell of a sports car, though. You may recognize the specs as being those of the imaginary, utopian flying car in the trip times chart back in chapter 11. Yet this was a machine that actually flew half a century ago.

A Resurgence

Convertible airplanes

Mark my word: A combination airplane and motor car is coming. You may smile. But it will come.

—Henry Ford (1940)



It is quite remarkable how many convertible airplanes have been built over the past 70 or so years. (See Appendix F. The phrase “roadable airplane” is also used, indeed more commonly than “convertible.” I tend to reserve “roadable” for folding or retractable wing types and use “convertible” as a more general term to include modulars. It makes little sense to call, say, the Darpa TX or the ConvAirCar a “roadable airplane;” the roadable part can’t fly and the flying part isn’t roadable.) I certainly had no idea how many had been built and flown until I began doing the research for this book. But they have been produced, both by companies and individual inventors, with almost monotonous regularity. There is clearly no major technical difficulty with the task. Henry Ford was completely right insofar as a combination aeroplane and automobile is perfectly feasible. We may smile yet.

In today’s world, even a non-Stagnated version, *the flying car is not a replacement for the car; it is a replacement for the airplane*. A reasonably well-designed convertible could fit right in to today’s airspace system; it would fit right into our road system as well. Without the Stagnation there might well be a 50,000 airplane per year market, and enough licensed pilots to buy them. Remember, *average* family income would be well into six figures. In 1950, about one quarter of one percent of Americans were licensed pilots; that percentage today amounts to over three quarters of a million, which is market aplenty, for a start.

Perhaps today the best ten percent of drivers could become pilots without introducing too much danger, which would essentially multiply the number

of active pilots by 100. Long before that point, however, the airspace and air traffic control system (not to mention ground access to airports) would have been completely overwhelmed and flying would be a rush-hour nightmare. But you don't have to revamp the ATC system simply to have currently flying planes be able to drive away after they land.

I might use a convertible for five to ten times as many (flying) trips as I do my current conventional airplane. One major advantage is that you don't get stranded by bad weather—you land and drive through it. Another is having a car when you get there. You skip shifting the luggage twice on the trip.

And you get to keep it in your own garage.

So convertibles seem to be the best evolutionary step from the current situation to the flying car. The design of the machine itself is by far the easiest of the innovations that would be necessary. Many of the others would involve regulatory reform and coordinated public action in many spheres, a considerably harder problem than building a gadget that drives and flies. On the other hand, convertibles could represent enough of an advantage to reverse the current slow decline of general aviation. *It is a possibility.*

Travel theory tells us that the best value-added of a convertible is not as a light sport aircraft, easy to learn and appropriate for joyrides; it is for longer trips at high speed. A helicopter that could do 100 knots and fly from your driveway would be worth two and a half times the value of your ground car; a convertible that did 300 knots (like the newly certified Cirrus small jet) but had to be driven 20 minutes to an airport would be worth five times. At that speed I could get to Orlando, Memphis, Chicago, or Montreal in about two hours; everything between Boston, Cincinnati, and Charleston, SC is less than an hour and a half. That is the travel regime in which the flying car would make a huge difference.

That tells us a lot about what today's convertible flying car would have been like, once market forces had pushed designs into the most valuable configurations. Imagine a highly streamlined car, some improbable blend of a Toyota Prius and a Lamborghini Huracán. It has smaller than average tires, because they are going to retract while in the air. On the ground the car has what looks like a roof rack full of surfboards. Wing loading is high, giving a longer takeoff and landing roll than a typical small private plane, but no more than a bizjet. [\[192\]](#) Wings and tail deploy at the push of a

button; modern sensors and computer monitoring are pressed into service for a more comprehensive pre-flight check than the pilot's walkaround. The other place where Twenty-first Century technology would come in is trip planning and navigation. Today a private pilot needs to do weather research, not just worrying about storms but headwinds and tailwinds aloft, which can make a big difference in times and fuel usage. An automated online system that got live weather data, planned an optimal route, and filed a flight plan would be invaluable. There are apps for tablet computers that do most of this today; real-time data-level integration into the ATC system is most of what's missing.

You drive to the nearest airport—without the Stagnation and GA crash they would probably be about five times as common and thus half the distance your nearest airport is now. The gates open automatically; airport fences are not only to keep the riff-raff out but to keep deer off the runway, a Very Good Idea. Drive slowly down the taxiway while the wings unfold; you've just saved fifteen minutes versus either untying and uncovering your plane or getting it out of a hangar. Off you go; reverse the process when you land, saving another quarter-hour. Simply drive away to your destination.



The recently-announced Terrafugia Transition plane has a different design from the convertibles of the 30s and 40s. Instead of taking off the wings and tail and towing them as a trailer, the wings fold in place. The use of a canard in front allows it not to need the tail extended the full length of the trailer—and 50 years of improvement in aerodynamic theory and simulation almost certainly helped, as well!

The Terrafugia's major limitations as a flying car have to do with its aircraft classification: because it was designed for an FAA classification as a light sport aircraft (which are easier to get pilots licenses for than general-class planes), it is only a two seater and only has a cruising speed of about 100 knots. But it is, as of date of writing, snarled in a regulatory morass: NHTSA automobile regulations push it over the weight limit for the FAA LSA regulations. [\[193\]](#) But the fact that the Terrafugia can be built today by a small start-up makes it almost certain that today's technology would be able to produce a real, usable, flying car, if we considered only the technology independent of price, regulation, and so forth. Another convertible, a Slovakian effort that has also actually flown, is the Aeromobil. Its wings swing back along the body, like a bee or beetle, instead of folding:



Like Terrafugia, Aeromobil appears to be a reasonably well-funded company with a good chance of technological success. How they will fare vis-a-vis the regulatory hurdles and the marketplace remains to be seen; they are debuting in the Canadian market, where the regulations are at least a little less insane than the US ones. *It is a possibility.* There is even a modernized version of the Pogo XVY, with a twist: DARPA and the Navy are developing a version of a tail-sitter VTOL for the same use the originals were proposed for back in 1954, but finessing the problem of tricky piloting and no rear vision by making it an autonomous drone:



The TERN autonomous tailsitter (DARPA / ONR)

The Drone Revolution

Even though the battery/electric power train is as yet too heavy for serious human-sized airplanes, recent advances have made it perfect for toys and unmanned drones. Advances in electronics have made sophisticated control computers and robust power-control circuitry a match for rare-earth magnet electric motors. The only part really missing is a good battery.

The electronic power train gives you several advantages in a VTOL. First is that you can have a number of smaller motors instead of one big one. The VTOLs of the 50s and 60s typically had transmissions and shafts from one or more engines to their various fans, because it would be disastrous to lose one. But modern electric motors are as reliable as the gearboxes were, which saves a lot of weight. Secondly, the motors have a much faster reaction time to power variations, which means that you can control the attitude of the craft with differential power, instead of needing articulated flapping rotors with collective and cyclic pitch control. The props can be smaller, much less complex, and not turn the whole machine into a gyroscope with unintuitive dynamics. Instead of needing a separate tail rotor to counter torque, half the motors turn one way and the other half the other. Net rotor torque gives you fast and precise yaw control.

Add autopiloting capabilities in the controller and you get the drone explosion of the past decade. It is probably the drone revolution more than anything else that has re-kindled interest in flying cars in the 21st century. There are at least 20 flying car start-ups, including the ones shown here. See Appendix F.

The possibilities enabled by the electric motor / small prop technology of the drones has not been wasted on designers of human-scale machines.

Increase the number, rather than the size, props:



Germany's Volocopter, on its first manned flight.

The Volocopter made its first manned flight in early 2016 with these comments from its test pilot:

“The flight was totally awesome” Alex Zosel said right after his landing. “The machine was absolutely reliable, there were no vibrations, it was tremendous. Anyway, the first flight was simply unbelievable. ... I simply pushed the lever upward and the Volocopter simply sprung upward in a single bound. ... It is definitely a sublime feeling to lift off, fly the first few meters, and then actually take my hand off the joystick and think that, yeah, it’s really as if I’m standing on the ground, and then I look down and there are 20-25 meters beneath me.”

The unstated pretext is that he is comparing the ease of control to a helicopter. The difference is of course full-time computer autopilot control of all the motors. Unlike a classic heli, the Volocopter is a machine that anyone who is a competent automobile driver could learn to use.

The single-passenger Ehang quadcopter is even more so; there are no internal controls at all, and the passenger simply selects a destination on a screen. The machine is flown by an autonomous autopilot with routing assistance from a control center on the ground.



The Lilium

The Lilium has flown as a full-sized model but without any people on board. Its configuration is somewhat more tuned to the demands of travel theory: it is VTOL but also designed to be able to use its thrust to go fast once in the air.

The main problem with all of these drone-derived flying cars is that they have all been designed to use batteries, at least in their prototypes. This is silly enough for an airplane of conventional design, but for a VTOL, with 2 to 5 times the power requirements, it's just nuts. The total flying time of these cool-looking new gadgets is often less than the FAA-required reserve time, leaving zero for the intended trip. On the other hand, replace the batteries with an APU turbine/generator set, and you have something much closer to a useful flying machine.

From 2016 to 2018 there was a DARPA-sponsored program to develop a ducted-fan VTOL under the name Aurora XV-24 LightningStrike. The XV-24 is very similar to the Lilium in configuration and appearance, but was to use a Rolls-Royce AE1107C turbine powering three 1-megawatt Honeywell generators instead of batteries. The program achieved success in a subscale demonstrator but was cancelled before the completion of the full-scale prototype. Its design parameters were a gross weight of 12,000 pounds and a cruise speed over 300 knots. Cut the weight and power by a factor of three and you have just the flying car you're looking for.

——Bottom Line——

We can put the reasons we don't have flying cars today into four major categories:

Human: They are too hard for the average driver to handle, or would be too dangerous if they did. Flying is less comfortable and scarier than ground cars.

Technological: The inability to fly low and slow, both for safety and to land in small spaces, were major impediments to the general adoption of private flying machines. They require higher power and more mechanical complexity than ground cars.

Legal/regulatory: Liability and regulation were insanely overdone, clobbering not only technological progress but already established industries.

Economic: Flying machines, starting with airplanes but particularly helicopters, are much more expensive than ground cars. Jets are more expensive than pistons.

Each of these categories trades off with the others. For example, you can finesse the low-and-slow problem by using a helicopter, but that makes it harder to fly (human) and more expensive (economic). You are thwarted in finding innovative technological solutions by the legal and regulatory constraints.

Any one of the categories, even any two, are fairly straightforward to solve in isolation. But all of them together form a game of Whack-a-Mole, where obvious solutions to one cause another to pop up more strongly. We have to find solutions to all of them at once before we get universal flying cars.

On the regulation front, what needs to be done is obvious, but how to do it remains completely obscure.

On the human factors dimension, any increase in automating the pilot's task will help. Any increase in wing loading will reduce the susceptibility of the craft to turbulence, and cabin pressurization will allow you to fly high over the weather. This changes a perhaps over-exciting barnstormer joyride into a luxurious passage in a private jet. But this puts the onus on technology.

On the technological front, there are many solutions to the above problems, but they cost money.

The bottom line economically is twofold: demand and supply. Flying cars have to be valuable enough that people want them. Helicopters are more valuable than cars, but travel theory shows us that they are only about two to three times as valuable, limited as they are to about 100 knots. They cost on the order of ten times as much. The real value comes with both low latency and high speed.

On the supply side, the bottom line is productivity. If our manufacturing technology is only good enough that everybody working full time could barely produce private jets for ten percent of the population—and it's not even that good now—Average Joe is not going to get a high, fast, VTOL jetcar. If on the other hand, if ten percent of the people working full-time could build private jets for everybody, then he does.

Call it a two orders of magnitude improvement. That's about what happened in the 19th century, giving us the family car, all the pundits and futurists of 1900 to the contrary notwithstanding. We can see the outlines of a second industrial revolution which could do it again: it is, of course, nanotech.

14 When Worlds Collide

WASTE ANYTHING EXCEPT

T I M E

TIME IS OUR SHORTEST MATERIAL

To answer the question regarding timespan, it seems that a 5-year development cycle with that instrument could get you to another plateau of capability; another 5-year development from that could get you a long way. I commonly answer that 15 years would not be surprising for major, large-scale applications.

—K. Eric Drexler, Senate testimony (1992)

Demandez quelque chose, mais le temps.
(Ask for anything, except time.)

—Napoleon to his generals

Imagine trying to do the opposite of nanotech, of trying to build enormously big machines. Call it gigatechnology. Now suppose the rules of the project were that you couldn't use your existing machines to build bigger ones, and those to build yet bigger ones, and so forth; you had to jump directly from existing technology to features that were at least a mile wide. Pretty much the only thing you could make would be mile-wide holes with nuclear explosives. Your notion of gigatechnology would pretty soon be warped into something along the lines of Project Plowshare in the 1960s, where they proposed digging canals and harbors, blasting new passes in mountain ranges, fracturing oil shales (!), dam construction, and creating underground caverns for natural gas storage.

That didn't work out so well.

As a member of the Foresight/Battelle *Roadmap to Productive Nanosystems* [\[194\]](#) working group, I was the champion of Feynman's

scheme as one of the possible pathways to molecular manufacturing. It was decided, however, that the Roadmap should focus only on those techniques which produced atomically-precise products. This seems a bit counter-intuitive, like insisting that the only area on a map be that of the destination and exclude the starting point and intervening territory. There were however sound political reasons for it, primarily as a hard stop to exclude the thin films and particulates “nanopants” nonsense from taking over the proceedings.

But now the time has long since come to examine the possibility of actually doing what Feynman proposed. You may, if you like, consider this the missing Roadmap chapter.

Self-replicating Machines

Leaping lightly across some centuries of intensive development and discovery, let us consider how the replicator would operate.

—Arthur C. Clarke, *Profiles of the Future*

So why hasn't the Feynman Path been attempted, or at least studied and analyzed? One possible reason is that there still seems to be a “giggle factor” associated with the notion of a compact, macroscale, self-replicating machine using standard fabrication and assembly techniques. Although studied in the abstract since von Neumann, and in physical systems in biology over roughly the same period, kinematic self-replicating machines remain poorly characterized as a field of engineering.

One reason for the giggle factor is that we have a strong instinct, well founded in experience, that in standard technology a factory is much bigger and more complex than whatever it makes. This instinct is neatly captured by a car factory, which is literally thousands of times bigger and more complex than the cars it produces. But the Feynman Path requires starting out with a self-replicating machine.

Consider this article by George Friedman, a professor of engineering at USC and Research Director of the Space Studies Institute: [\[195\]](#)

I can't repeat the many times I've been reassured that self-replication was easy. After all, John von Neumann, way back in the 40's, clearly defined the logic of self-replication and all we have to do is implement his “blueprint”. His automata theory anticipated the later research on biological reproduction. In the early 1980's, there was a flurry of activity—especially the Robert Freitas papers and the NASA summer study of 1980 [\[196\]](#)—which strongly advocated that NASA should embark on a new technological strategy, embracing automation, robotics and self-replication. In 1985, after Tihamer Toth-Fejel showed him the 1980 NASA summer study, Gregg Maryniak wrote an excellent article on SRSs in the SSI Update. Recently two rather optimistic books on the emerging field of Artificial Life were

published: Steven Levy's *Artificial Life* and Claus Emmeche's *The Garden in the Machine*. Within this past year, Lackner and Wendt, obviously inspired by chapter 18 of Freeman Dyson's *Disturbing the Universe*, published the paper with the exciting title, "Exponential Growth of Large Self-Reproducing Machine Systems".

Furthermore, it seems apparent to me that of all the processes that we observe in the biological world, self-replication is relatively easy. Despite the "inevitability reassurances" of Stuart Kauffman and Christian de Duve, I view the origin (or origins if you wish) of life as incredibly hard. If autocatalysis and other spontaneous appearances of great complexity are so inevitable, why can we not observe them in nature or in the laboratory? Biological self-replication on the other hand can be observed any time we choose to look. Other processes such as homeostasis, morphogenesis, epigenesis, endosymbiosis, evolution, cognition, consciousness and conscience are, in my opinion, also far harder than self-replication.

And finally, engineering designs can learn from biology, but certain practical simplifications are possible (and desirable to reduce cost and complexity) as we try to apply SRS [Self-Replicating Systems] to space colonization. For example, we need not go to the trouble of incorporating the blueprint for the entire system into every subsystem. We need not assemble the system in a tortuous series of incremental developments which recapitulate earlier design generations. We need not design for inheritable mutations. Indeed, as we concentrate on the colonization of the solar system, we can practically maintain all genetic control of all space-borne self-replicating systems by human scientists and engineers on Earth. Essentially, as Ralph Merkle puts it, we can "broadcast" the genetic information from Earth rather than encode it within the generations of SRS.

So if self-replication is so easy, where are all the SRSs?

On a personal note, I was in a discussion of nanotech in a long-view futurist setting around the turn of the century which also included Mark Reed of Yale, a top academic nanotech researcher. I had finished describing the possibilities of atomically-precise motors, gears, shafts, pulleys, and the

rest, and mentioned that I was quite certain we'd have them sometime in the 21st century. The moderator was somewhat incredulous, and asked Reed if he believed that, to which Reed replied (in my certainly not verbatim recollection) that of course we would, but that they wouldn't be able to self-replicate.

One reason for this skepticism, and indeed of the difficulty of KSRMs (kinematic self-replicating machines, to distinguish them from cellular automata or other self-replicating models) in the first place, is that KSRMs defy standard design methodologies. In standard top-down design, a critical part of the specifications for a machine is its capabilities; to design a manufacturing system, for example, it is useful to know what it must manufacture. For a self-replicating system, however, the product is the system itself, the specifics of which are not known until the design is completed. Therefore the design process more closely resembles the solution of a system of equations by iteration or relaxation, than the one-pass evaluation of a closed formula.

The majority of published KSRM designs have either required complex subsystems as "raw material," resulting in greatly over-simplified construction capabilities, or have foundered on extreme system complexity because of a requirement to use naturally occurring raw material inputs (*e.g.* the 1980 NASA study). The prevalence of these extremes has led to a perception that there was no practical middle ground between them. It may be, however, that there are the beginnings of a shift on the subject. One reason is RepRap, an open-source project to design a self-replicating 3D printer. It has demonstrated that the capabilities of a 3D printer could actually be useful in a self-replicating system. (RepRap is about a quarter of a self-replicating machine—it makes about half its own parts, and making its parts is about half the problem, the other half being assembling them. But it does represent something of a conceptual breakthrough with respect to the giggle factor.) It seems clear that a major step toward the Feynman Path would be to work out a scalable architecture for a workable KSRM that actually closed the circle all the way. A reasonable start would be an additive manufacturing machine, a multi-axis mill for surface tolerance improvement, and a pair of waldos. See how close you could get to replication with that, and iterate.

There are plenty of other problems, but this would at least give us a framework to address them in. *It is a possibility.*

Everything is theoretically impossible, until it is done. One could write a history of science in reverse by assembling the solemn pronouncements of highest authority about what could not be done and could never happen.

—Heinlein

MEMS

Another reason the Feynman Path may not have been tried is the perception that a machine-based approach had already been tried in the form of MEMS (micro-electronic and mechanical systems), and that standard machine designs do not work at this scale and below due to stiction.

MEMS are in fact crippled by this phenomenon, which is a essentially an enormous increase of friction with decreasing scale. This is, however, to a great extent because MEMS have very poor tolerances: "... in traditional machining, relative tolerances of 10^{-6} are becoming standard, whereas in the integrated circuit industry, a 10^{-2} relative tolerance is considered good. The definition of precision machining, with relative tolerances of 10^{-4} , actually excludes micromachining!" A full machining and manipulation capability at the microscale would allow lapping, polishing, and other surface improvement techniques, which photolithography-based MEMS does not.

Feynman understood the key importance of precision:

If you work through a pantograph, even today, you can get much more than a factor of four in even one step. But you can't work directly through a pantograph which makes a smaller pantograph which then makes a smaller pantograph—because of the looseness of the holes and the irregularities of construction. ...

At each stage, it is necessary to improve the precision of the apparatus. If, for instance, having made a small lathe with a pantograph, we find its lead screw irregular—more irregular than the large-scale one—we

could lap the lead screw against breakable nuts that you can reverse in the usual way back and forth until this lead screw is, at its scale, as accurate as our original lead screws, at our scale.

We can make flats by rubbing unflat surfaces in triplicates together—in three pairs—and the flats then become flatter than the thing you started with. Thus, it is not impossible to improve precision on a small scale by the correct operations. So, when we build this stuff, it is necessary at each step to improve the accuracy of the equipment by working for awhile down there, making accurate lead screws, Johansen blocks, and all the other materials which we use in accurate machine work at the higher level. We have to stop at each level and manufacture all the stuff to go to the next level—a very long and very difficult program.

We know, of course, that it is possible to create more precise machines using less precise ones: our entire industrial base got built *somehow* in a chain of machines that stretches back to the days when blacksmiths shaped tools by beating them with hammers. Those of you who are avid enough amateur astronomers know that you can grind your own telescope mirrors by hand to a precision much, much higher than your hand motions can actually achieve.

In other words, the Feynman Path does not envision simply building a factory which can spit out another factory at quarter-scale and quarter tolerance as if it were stamping out consumer goods. It will require attention and craftsmanship at each level, and indeed probably significant experimentation and the development of new techniques in many cases. But—and this is a mantra I have repeated often—at each stage we will have the full fabrication and assembly capability we need to do experiments, build instruments, and invent and test novel techniques. It is difficult to overstress how valuable it will be to maintain this capability, taken for granted at the macroscale, at each step to the nanoscale.

Is it Worth Starting Now?

Surely, you will say, it would have been wonderful if back in 1960 people had taken Feynman seriously and really tried the Feynman path: we'd have

the full-fledged paraphernalia of real, live molecular machinery now, with everything ranging from countertop replicators to cell-repair machines. After all, it's been 55 years. The 10 factor-of-4 scale reductions to make up the factor-of-a-million scale reduction from a meter-scale system with centimeter parts to a micron-scale system with 10-nanometer parts, could have been done at a leisurely 5 years per step—plenty of time to improve tolerances, do experiments, invent new techniques.

But now it's too late. We have major investment and experimentation and development in nanotech of the bottom-up form. We have Drexler's PNAS paper telling us that the way to molecular manufacturing is by protein design. We have a wide variety of new techniques with scanning probes to read and modify surfaces at the atomic level. We have DNA origami producing arbitrary patterns and even some 3-D shapes. We even have protein engineering producing the beginnings of usable objects, such as frames and boxes.

Surely by the time a Feynman Path, started now, could get to molecular scale, the existing efforts, including the pathways described in the *Roadmap for Productive Nanosystems*, would have succeeded, leaving us with a relatively useless millimeter-sized system with 10-micron sized parts? No—as the old serials would put it, a thousand times no.

To begin with, a millimeter-sized system with 10-micron sized parts is far from useless. Imagine current-day MEMS but with the catalog and capabilities of a full machine shop, bearings that worked, sliders, powerful motors, robot arms and hands. The medical applications alone would be staggering. High-precision machining has not stood still since the 50s. In fact, the *starting point* today might well be a millimeter-sized system with 10-micron sized parts. Existing nano-positioning stages have 50 picometer resolution; existing microgrippers can manipulate parts down to 1 micron; electron-beam lithography can cut with precision in the 10-nanometer range. The bottom-up folks are not nearly as close to real nanotech as the impression the nano-hype news gives. When a researcher announces a nano-transistor, it means he poked at nanotubes with an STM for 5 months and got 17 usable structures, of which 3 worked reliably.

More to the point, a mature technology will need to be able to work at all scales anyway. Imagine that you have a watchmaker's loupe and a set of tweezers that let you manipulate 1-millimeter grains of sand precisely. To

do the equivalent of making, say, a flying car atom by atom, you would be set the task of building an object the size of the Earth—ten billion parts across. You are going to need a few trucks, at the very least, to augment your tweezers.

Top-down and bottom-up can meet in the middle. When nanoscientists succeed in making an atomically precise nanogear, for example, it means that when the Feynman Path machines get to that scale, they can take the gear off the shelf instead of having to fabricate it the hard way. In fact it seems likely that the bottom-up approaches will likely be the way parts are made and the top-down the way they're put together. I'll stick my neck out and say at a wild guess that if only bottom-up approaches are pursued, we have 20 years to wait for real nanotech; but if the Feynman Path is actively pursued as well, it could be cut to 10.

It is a very long and very difficult program—but it is a possibility.

Open Questions

Taking Feynman's Path to nanotech, or even studying it seriously, would require finding answers to a number of open questions. These questions, however, are quite important and knowing the answers will be invaluable in understanding the envelope of possibilities for future manufacturing technology.

Is it in fact possible to build a compact self-replicating machine using macroscopic parts-fabricators and manipulators? We know that a non-compact one is possible—the world industrial infrastructure can replicate itself—and we know that a compact microscopic replicator can work, e.g. a bacterium. But the bacterium uses diffusive transport, associative recognition of parts by shape-based docking, and other complexity-reducing techniques that are not available at the macroscale.

Not quite the same question: how much cheating can we get away with? In KSRM theory, it's common to specify an environment for the machine to replicate in and some “vitamins,” bits that the machine can't make and have to be provided, just as our bodies can't synthesize some of the molecules we need and must get them pre-made in our diets. For the purpose of the Feynman Path, we can cheat in a very legitimate way: any part or capability that can be provided on whatever scale it's needed from the outside, is fine.

We start with control signals—no autonomous AI necessary! If we synthesize molecular gears by chemistry, wonderful. If we can provide single-crystal chunks of silicon or diamond to carve, do it. If we can polish surfaces with low-angle e-beams, wonderful. What's left for our machine to have to make? What are the roadblocks we'll have to invent our way around? The classic example is that electromagnetic motors work poorly at small scales, so we have to shift to electrostatic ones. Here are some others (by no means a complete list):

- Near the atomic scale, we hit an “ontological phase boundary” where we have to quit thinking of our material as continuous (and able to assume arbitrary shapes, like circles) and start treating it as discrete and lumpy.
- Gravity essentially vanishes, but the adhesion of parts to each other increases tremendously.
- Lubrication by oily fluids quits working. An oil molecule is an object, not a fluid.
- Heat dissipation rates increase as surface/volume ratios do.
- Nothing is stiff; even diamond acts like a fairly springy plastic.
- Hydrogen atoms can jump from point to point without being anywhere in between, by quantum-mechanical tunneling. (Luckily, other atoms are too massive to tunnel under most circumstances).
- ... and so forth.

What kinds of forming techniques will work? There are a number of solid free-form fabrication technologies at the macroscale, which can in theory be adapted to smaller-scale forms where molten droplets, or whatever, are replaced by mechanochemical deposition tips. At larger scales, for decent tolerances, SFF must be followed by surface finishing. Will this work all the way down?

And finally, how do we see what we're doing? It's all very well for Heinlein to talk about scanners, but existing techniques like scanning probes only work over relatively flat surfaces, not in the crowded interior of a milling machine or the like. We'll probably have to build physical surface scanners—but existing shop practice makes extensive use of physical contact measurement anyway, so this probably won't be such a major change.

Plan of Attack

The difficult we do immediately. The impossible takes a little longer.

—Motto of the SeaBees

There are at least two major parts to a project to implement the Feynman Path. The first is essentially to work out a roadmap for the second. In particular,

- Design a scalable, remotely-operated manufacturing and manipulation workstation capable of replicating itself anywhere from its own scale to one-quarter relative scale. As noted before, the design is allowed to take advantage of any “vitamins” or other inputs available at the scales they are needed.
- Implement the architecture at macroscale to test, debug and verify the design. This would be a physical implementation, probably in plastic or similar materials, at desktop scale, and would include operator controls that would not have to be replicated. Identify phase changes and potential roadblocks in the scaling pathway and determine scaling steps.
- Verify scalability of the architecture through these points in simulation. Example: electromagnetic to electrostatic motors. It would be perfectly legitimate to use externally supplied coils above a certain scale if they were available, and shift to electrostatic actuation, which would involve only conducting plates, below that scale, and never require the system to be able to wind coils.
- Identify the smallest scale, using best available fabrication and assembly technology, at which the target architecture can currently be built.
- Write up a detailed, actionable roadmap to the desired fabrication and manipulation techniques at the nanoscale. Note that the state-of-the-art “starting point” that would be the bootstrap of the actual scaling series, has nothing to do with the scale (or materials) at which the conceptual debug system would be implemented. The debug system would be at a

scale where the parts are easily handled by hand, both to facilitate experimentation and to make the best use of physical intuition in the design process. It would use materials, probably plastics, whose mechanical properties at the macroscale would best simulate those of the expected materials available at the nanoscale. The starting-point system, on the other hand, might begin with a particularly stiff material (e.g. electro-discharge machined tungsten carbide) to have as little ground to make up in moving to diamondoid or the like at the nanoscale.

Building a real, physical system is valuable in a number of ways. It is far too easy to make assumptions in modeling and simulation that the recalcitrant real physical world refuses to agree with. Building a working physical model would yield significant insights into necessary capabilities, reveal bugs and design shortcomings, and serve as an experimental platform for proposed improvements.

It would also go a long way to lay to rest objections about the possibility of KSRMs, and serve as a solid experimental datapoint for further KSRM theory.

Where to Start?

Finding the appropriate starting point is one of the critical items to address in forming a Feynman Path roadmap. A thorough survey of available techniques should be made, and recent advances in machining, nanomanipulation, and so forth taken advantage of.

However, as a point of reference, at least one experiment has been made, in a sense, which suggests that a 1/1000-scale system might be achievable (as compared to the desktop-scale prototype with finger-size parts). To quote from Freitas and Merkle's encyclopedic *Kinematic Self-Replicating Machines*: [\[197\]](#)

[I]n 1994 Japanese researchers at Nippondenso Co. Ltd. fabricated a 1/1000th-scale working electric car. As small as a grain of rice, the micro-car was a 1/1000-scale replica of the Toyota Motor Corp's first automobile, the 1936 Model AA sedan. The tiny vehicle incorporated

24 assembled parts, including tires, wheels, axles, headlights and taillights, bumpers, a spare tire, and hubcaps carrying the company name inscribed in microscopic letters, all manually assembled using a mechanical micromanipulator of the type generally used for cell handling in biological research. In part because of this handcrafting, each microcar cost more to build than a full-size modern luxury automobile. The Nippondenso microcar was 4.8 mm long, 1.8 mm wide, and 1.8 mm high, consisting of a chassis, a shell body, and a 5-part electromagnetic step motor measuring 0.7 mm in diameter with a ~ 0.07 -tesla magnet penetrated by an axle 0.15 mm thick and 1.9 mm long. Power was supplied through thin (18 micron) copper wires, carrying 20 mA at 3 volts. The motor developed a mean torque of 7×10^{-7} N-m (peak 13×10^{-7} N-m) at a mean frequency of ~ 100 Hz (peak ~ 700 Hz), propelling the car forward across a level surface at a top speed of 10 cm/sec. Some internal wear of the rotating parts was visible after ~ 2000 sec of continuous operation; the addition of ~ 0.1 microgram of lubricant to the wheel microbearings caused the mechanism to seize due to lubricant viscosity. The microcar body was a 30-micron thick 20-milligram shell, fabricated with features as small as ~ 2 microns using modeling and casting, N/C machine cutting, mold etching, submicron diamond-powder polishing, and nickel and gold plating processes. Measured average roughness of machined and final polished surfaces was 130 nm and 26 nm, respectively. The shell captured all features as small as 2 mm on the original full-size automobile body. Each tire was 0.69 mm in diameter and 0.17 mm wide. The license plate was 10 microns thick, 0.38 mm wide and 0.19 mm high.



Nippondenso Micro-Car

In other words, it's pretty clear that the technology exists today to manipulate micron-scale parts, and to make parts with a few tens of

nanometer roughnesses (not the same as tolerance, but just as important in many cases). It's important to note that the Nippondenso Microcar had relative tolerances more like MEMS than high-precision machining. However, given the techniques developed since 1994 in aid of mainstream nanotechnology, it's very likely that considerably finer tolerances (and roughnesses) are possible today. If so, we could start the Feynman Path halfway down—at 1/1000 scale. Another factor of 1000—just 5 of Feynman's steps!—and we have flat-out nanotech.

Scaling KSRM Design Considerations

There hasn't been a lot of work on self-replicating workcells. There's been plenty on robotic workcells that don't replicate, but almost all of this falls into the “more complex than what it makes” category. The basic idea goes back to *Waldo*: imitate a machine shop and the person servicing the machines / assembling the parts.

I used the idea of a general-purpose manipulation robot in my early nanotech designs, [\[198\]](#) but this is probably more complex than would be needed for the Feynman Path. The difference is that the system in the paper was geared for producing significant amounts of product as well as reproducing/extending itself. We could probably get away with just a pair of arms on a rotating base with access to a few machines and a workbench (for assembling more machines).

A Feynman Path workcell actually avoids the problem that a standard 3D printer design has with building something its own size, because it's building a copy that's smaller than itself! Even so, it will have to have general manipulation capability—and the target system, at the nanoscale, will have to build more copies at its own size, so we can't go with just a simple 3D printer design.

Even so, additive manufacturing is the key to giving the replicating system a manageably small size. It's the main technology that wasn't here in Heinlein's and Feynman's day. The key to using it in a scaling sequence is to understand what kinds of depositions could be done at different stages. One of the most straightforward at the macroscale is melting the substance of interest and allowing it to cool as you deposit essentially drop by drop on the workpiece. This works for materials ranging from wax to titanium.

Scaling works both for and against us here—the super-fast dissipation of heat at smaller scales means you have greater control in time, but less in space, of what melts.

At smaller scales, electrodeposition (and electro-removal, as in EDM) will likely have to be used. At the smallest scales, the processes used in electroplating, but controlled at the near-atomic scale, are good candidates. Nanotech enthusiasts have done considerable study of the chemistry of single-molecule deposition reactions in simulation, mostly for diamond synthesis.

A particularly important aspect of the Feynman Path is that not much more than halfway down to molecular scale in part size, we already hit atomic scale in tolerance. That's within a generation or two from our likely starting point at 1/1000 scale. A micron-sized part really needs atomic-scale tolerance to be considered high-precision. Thus much of the work in that size range will be aimed at surface forming or re-forming. Even so, there will be a pressure to design machine elements where bearing surfaces are flat (as in a thrust bearing or slider) so they can follow crystal planes, until such time as it becomes possible to construct strained-shell circular bearings (simple example: “multi-walled carbon nanotubes”).

——Bottom Line——

I find it incredible that there will not be a sweeping revolution in the methods of building during the next century. The erection of a house-wall, come to think of it, is an astonishingly tedious and complex business; the final result exceedingly unsatisfactory. ... Better walls than this, and better and less life-wasting ways of making them, are surely possible. ... I can dream at last of much more revolutionary affairs, of a thing running to and fro along a temporary rail, that will squeeze out wall as one squeezes paint from a tube, and form its surface with a pat or two as it sets.

—H. G. Wells, *Anticipations* (1902)

Estimates for the size and growth of the market for Additive Manufacturing hardware and services vary widely, but across the board all suggest varying degrees of rapid growth. According to IBISWorld, U.S. based suppliers of 3D printers and related services generated combined revenue of \$2.4 billion in 2012, which is expected to grow nearly 14% annually through 2017.

—GEcapital.com

“Solid freeform fabrication,” popularly known as 3D printing, is one of the technologies made newly viable by the advances in processing power and sensors. It has clearly reached a takeoff point and will form an increasingly important part of the industrial base and the global economy. Jeff Immelt, chairman and CEO of GE, writes:

Manufacturing is the new basis for competitive advantage for industrial companies and for that matter countries. The notion of manufacturing has changed and the era of labor arbitrage is ending. You can make whatever you want, whenever you want. Entrepreneurs inhabit the manufacturing space like never before. Manufacturing is being digitized, decentralized and democratized.

The main drivers of the change since the days of the early stereolithography machines that slowly printed shapes in somewhat fragile plastic are the cost of the machines, which has been plummeting, and the variety and quality of the materials of the printed objects, which has been rising just as rapidly. There are machines which print “digital materials,” that is, programmably variable combinations of the basic materials available. This allows the designer to specify a wide range of material properties, and indeed have them vary across the object: for example, a rod that is hard on one end and rubbery on the other, changing smoothly along its length.

It’s not hard to imagine the kinds of improvements that additive manufacturing will see over the next decade or two. The speed of big commercial machines will increase, and the cost of personal ones will come down. Range of materials will increase. Precision will get better. We will get closer and closer to being able to print out anything that can be manufactured today—“whatever you want, whenever you want”—and let us add “wherever you want.” This means not just plastic, or even metal shapes, but working machines. Ultimately even working 3D printers.

Although classic SF writers didn’t quite get nanotech as the way replicators would work, they did realize that personal-sized replication could have a major economic, and thus social, impact. The best-known examination of this was in George O. Smith’s *Venus Equilateral* stories, where the invention of a replicator causes a major economic crash and the breakdown of civilized society.

We have several examples of individualized technology overtaking centralized ones. Cars overtook trains. Cell phones overtook land lines. One-hour photo shops overtook sending your film to Rochester to be developed. Digital cameras overtook one-hour photo shops. PCs overtook the horridly bureaucratic corporate (and university) computer centers, and reduced the cost of computing by a factor of a billion. In no case did the world fall apart.

Instead it seems likely that the nanomanufacturing revolution will resemble the computer revolution in many ways, and will have many of the same kind of salutary effects as far as personal autonomy and the enhancement of creativity. I would say that there were on the order of 100 software applications available to computer users in the big computer centers where I did my work as a student in the 1970s; there are 1.5 million apps for your

smartphone today. Imagine the same “Cambrian explosion” with physical machine types.

Norwegian archaeologists [\[199\]](#) recently uncovered a woolen tunic that had been abandoned on a trail across the Lendbreen glacier 1700 years ago.

They were surprised to find something so valuable that had apparently been simply left. In order to give their audience a sense of how valuable it was in the day, the archaeologists made a film in which they recreated the process that the people of year 300 would have used to make it. This involves hand-picking the wool from sheep who were shedding their coats, and hand-spinning thread, and weaving using a primitive loom, followed by cutting and sewing and so forth, all with the simplest of hand tools.

The total amount of labor necessary to create one tunic worked out to be three months of full-time work. At the average wage in the US, that would make the tunic cost \$15,000. In contrast, one can go on Amazon today and get an equivalent woolen tunic for \$50, or two and a half hours’ work. The difference, of course, is the Industrial Revolution. Using the machines invented in the meantime, each hour of human labor today produces 300 times as much as it did seven centuries ago. Your medieval counterpart would spend a year to make as much as you make in a day.

The promise of nanotech is that that could happen again. Things that now take us a year’s work could be done in a day. And your \$3 million flying car costs just \$10,000.

It is a possibility.

15 Failure of Feedback

In the 40s and 50s, there were the beginnings of a science that attempted to unify some of the knowledge we have of feedback in nervous systems, machines, and social structures. It was called cybernetics. It was well-understood by many of the Golden Age SF writers—notably, Isaac Asimov wrote the preface to the best of the popular histories and expositions of the field, [\[200\]](#) saying, “Cybernetics is not just another branch of science. It is an Intellectual Revolution that rivals in importance the earlier Industrial Revolution.” To the extent that he and the other SF writers believed that, it formed a reasonable basis for expectations of improvements in control systems ranging from robots to governments. If you read carefully between the lines in his robot stories, it’s clear that Asimov’s notion of the internal design of a “positronic brain” was much more like cybernetics than the later symbolic AI.

The relation of cybernetics to AI is an instructive, if unfortunate, example of the kind of factionalism that sometimes energizes, and sometimes destroys, scientific research. The origins of cybernetics came in the 40s, when there grew up a collaboration between neuroscientist Warren S. McCulloch and logician Walter Pitts, who had done groundbreaking work in showing the kind of things that neural network systems (then called *perceptrons*) could do, and mathematician Norbert Wiener, who had done much to revitalize and extend classic control theory with the notion of model-based “filters” (progenitor of the “Kalman filters” that are a part of every GPS and robot in the world today).

The collaboration between these two branches of inquiry proved very fruitful and promising. Cybernetics attracted a worldwide following of diverse intellectual figures ranging from John von Neumann to Margaret Mead. Wiener’s book *Cybernetics*, published in 1948, was improbably for such a technical book, a bestseller.

But in the early 50s, the Wiener-McCulloch collaboration imploded in a soap opera of internal backstabbing. [\[201\]](#) This was not immediately apparent from the outside, and cybernetics coasted for the next decade without the force of its main drive. In the same period, however, the digital world took off in a big way. Shannon’s digital information theory

superseded Wiener's analog one (Shannon had been a student of Wiener). By the time I began to study computer science in the Seventies, the theoretical foundations had shifted completely away from anything based in neural circuitry, to metamathematics and symbolic logic. In particular, feedback as a major organizing principle had almost entirely disappeared. A number of the early AI pioneers, notably Marvin Minsky and Oliver Selfridge, had a foot in both camps. But as digital and symbolic computation took off, there was no satisfying answer from cybernetics. There could have been. By 1969, Minsky had published an analysis of perceptrons that was generally taken as finishing them off as a useful AI device, and the field followed suit by ignoring them for a couple of decades. But in the 80s, psychologists James McClelland and David Rumelhart published a learning algorithm for multi-level neural networks, called back-propagation, missed in Minsky's analysis. Neural networks are essentially multiple layers of perceptrons, modified slightly so that a little information about the input leaks through along with the unit's main decision. As you might guess from its name, back-propagation contained a form of feedback. This revitalized the field substantially. The neural network field continued to labor as a red-headed stepchild of mainstream, algorithmic, symbolic AI, until the twenty-first century. There was something of a Machiavelli Effect. Geoffrey Hinton, a long-time champion of the approach, said,

People were very, very much against this stuff. Things were tough then. But my view was, the brain has to work somehow, and it sure as hell doesn't work the way normal computer programs work, and in particular, the idea that everything has to be programmed into AI is crazy. You interact with the world, and you figure out how the world works. It seemed to me the only hope to getting a lot of knowledge into an AI system was to develop learning algorithms that allowed them to learn this knowledge. That approach in the long run I thought was the only one with any hope of success. And it turned out I was right.

In 2009, Hinton's working group at U. of Toronto built the first deep neural net that had better speech recognition than the best algorithmic approaches,

but the word-error rate was still about 26%. In 2012 a new version got that down to 16%. In the intervening very few years, the powers that be in AI quit inveighing against neural nets and started experimenting with them. The current best recognition word-error rate is about 4%. “Deep Learning” in neural nets is now the hottest of the hot buzzword/techniques in AI. Cybernetics ultimately splintered into control theory, information theory, computational neuroscience, neural networks, artificial intelligence, and philosophy of mind. Much of the progress in robotics and machine learning in the 21st century has come from feeding back into our systems the insights of cybernetics.

The World of Null-A

I can go into my office and pick up the telephone and in twenty-five minutes seventy million people will be dead.

—Richard M. Nixon

To understand the political situation here, you must reach out with all your mind to the furthest limits of your ideas of ultimate democracy. There is no president of Venus, no council, no ruling group. Everything is voluntary; every man lives to himself alone, and yet conjoins with others to see that necessary work is done.

—A. E. van Vogt, *The World of Null-A*

“Two years after he arrived, the Nipe was almost caught. He had managed, somehow—we’re not sure yet exactly how—to get here from Asia. According to the psychologists who have been studying him, he apparently does not believe that human beings are any more than trained animals; he was looking then—as he is apparently still looking—for the ‘real’ rulers of Earth. He expected to find them, of course, in Government City. Needless to say,” said the colonel with a touch of irony, “he failed.”

—Randall Garrett, *Anything You Can Do*

Of all the great improvements in know-how expected by the classic science fiction writers, competent government was the one we got the least. The physical or intellectual technologies that were proposed for accomplishing the feat were wildly varied: For H. G Wells and the Scientific Socialists, it was centralized control of the economy, although exactly how this was supposed to work was never particularly well specified. Asimov has positronic brains running the economy in his stories. He also has a new science, psychohistory, that allows more rigorous prediction of the effect of some action or policy. Heinlein’s *Revolt in 2100* likewise has a science of

semantics that allows for precise technical analysis and control of propaganda, and a competent science of economics. In H. Beam Piper's Terro-Human history series, there is a veridicator, essentially a lie detector that really works, commonly used in government and legal matters, and a computer with the predictive powers of Asimov's psychohistorians. In his Paratime series,

“We define people as criminals when they suffer from psychological aberrations of an antisocial character, usually paranoid—excessive egoism, disregard for the rights of others, inability to recognize the social necessity for mutual coöperation and confidence. On Home Time Line, we have universal psychological testing, for the purpose of detecting and eliminating such characteristics.”

In other words, the science of understanding how the brain works has advanced to the point of being able to detect, and even to fix, sociopathy in individuals, which is assumed to be the major source of corruption in democracy and bureaucracy.

In E. E. Smith's *Lensman* series, the gadget is a *deus ex machina*, or more precisely *machina ex deus*, the Lens given to the Earthmen by the godlike Arisians which can guarantee that someone you put in power is utterly honest, well-intentioned, competent, and incorruptible.

A. E. van Vogt's *World of Null-A* actually has all three. There is “the Machine,” a giant computer which selects all the people who will hold positions of power and trust; there are “lie detectors,” which are common household appliances which are fully intelligent and able to read human memories; and there is “Null-A” itself, which is a fanciful inflorescence of a philosophy and intellectual technology based on Alfred Korzybski's General Semantics. It turns out that a large number of the mid-century American science fiction writers were fans of Korzybski; the ideas, and sometimes explicit references, show up throughout van Vogt, Heinlein, Asimov, Piper, and many other authors' works. One major reason was that John W. Campbell, the great editor whose tenure at *Astounding* essentially defines Golden Age science fiction, urged it on them with the idea that it was a prototype of what future logic and scientific thinking would be like

(and that future logic and scientific thinking would be much more capable and competent than old-fashioned “Aristotelian” logic and science).

And the most important place to use that improved decision-making ability, obviously, was government—and that was scientific socialism in a nutshell.

Most of the visions of the way the world should work in mid-century science fiction could trace their roots back to Bellamy’s utopian America and Wells’ “university planet” in *Men Like Gods*: E. E. Smith’s Norlamin; A. E. van Vogt’s *Null-A Venus*; Asimov’s *Foundation* Terminus; Heinlein’s future America in *For Us, the Living*; Clarke’s final-stage Earth in *Childhood’s End*.

Could there be a science of control and feedback that allows us to engineer competent governance systems? The SF writers in the Fifties thought so, as did most of the pundits and intellectuals of the day. The general background belief was that there had been a straight line upward from Runnymede to WWII, that the advance of western civilization and the advance of physical science were one, and that we would all have peace, prosperity, and flying cars Real Soon Now. It is not so clear that they were right. With the physical technological advances, they had centuries of substantial progress to look back on. The physical science and technology of ancient Greece and Rome were laughably primitive compared to ours. Their politics, however, were quite recognizably similar. In other words, there has been no history of progress in “leadership,” no secular trend of advancement that we can extrapolate upward. Released from its evolutionary pressures, the apparent sequoia of Western Civilization dissolved into a thicket of brambles and weeds.

On the other hand, the basic understanding of feedback that formed the basis of cybernetics came from our exploding knowledge of, and experience with, physical machines, ranging from the mechanically-linked spinning-balls Watt governor on steam engines to the electronic radar-linked gun-aiming servomechanisms we had (thanks in part to Wiener) by the end of WWII. Many of the schemes or gadgets for utopian governance in science fiction were really just fantasy and cannot be taken as reasonable predictions. With cybernetics, however, they were on firmer ground. We probably have to classify cybernetics, like flying cars, as something the SF writers understood fairly well and that we could quite reasonably have

today, and look for reasons beyond “they just got it wrong” that it didn’t happen.

Artificial Stupidity

There are now in the world machines that think, that learn and that create. Moreover, their ability to do these things is going to increase rapidly until, in a visible future, the range of problems they can handle will be coextensive with the range to which the human mind has been applied.

... within ten years a digital computer will be the world's chess champion... will discover and prove an important new mathematical theorem ... will write music that will be accepted by critics as possessing considerable aesthetic value.

—Newell and Simon (1958)

In from three to eight years we will have a machine with the general intelligence of an average human being.

—Marvin Minsky (1970)

The man of system, on the contrary, is apt to be very wise in his own conceit; and is often so enamoured with the supposed beauty of his own ideal plan of government, that he ... seems to imagine that he can arrange the different members of a great society with as much ease as the hand arranges the different pieces upon a chess-board.

—Adam Smith, *Theory of Moral Sentiments* (1759)

I will argue that artificial intelligence as now conceived is limited to a very particular kind of intelligence: one that can usefully be likened to bureaucracy in its rigidity, obtuseness, and inability to adapt to changing circumstances.

—Terry Winograd (1990)

The curious task of economics is to demonstrate to men how little they really know about what they imagine they can design.

—(Economics Nobel Laureate) Friedrich A. Hayek

The early pioneers of AI were famously over-optimistic about how quickly and easily we would be able to write computer programs with human-level understanding and judgement. It's interesting to compare their predictions to those of a science fiction writer such as Isaac Asimov, whose 1964 prediction for the state of robotics 50 years later (i.e. now) got it just about exactly right.

People closer to the details of the field often have a harder time seeing the forest for the trees. This can be especially true if they have just managed to cut down one of the larger trees themselves. If you are part of a major advance in a field like AI, it's easy to imagine that the remaining problems, which tend to look smaller in the distance, will fall to a similar amount of effort. Newell and Simon wrote in the days when they, and the other pioneers, had just invented symbolic computing; computers could now do logic and reasoning and not just arithmetic. Minsky wrote after his student Winograd had produced a landmark advance in language understanding.

Winograd himself, in the passage quoted, wrote after two decades of stubborn plateau following the heady advances of the early days.

Back in the Sixties when AI was having its first heyday, the typical machine used for the programs had about a megabyte of memory, a MIPS of processing power—and cost a million dollars. This was impressively more than had been available before, and perhaps the AI pioneers can be forgiven for imagining such a machine might do a human's amount of thinking.

Perhaps. Such a machine can just about simulate one neuron's signal processing in real time. Your brain consists of 86 billion neurons. [\[202\]](#)

We can make a reasonable argument that the brain is not 86 billion times bigger than it needs to be, or even 86 times bigger. The big human brain is evolutionarily costly: it makes us physically fragile; it uses quite a lot of energy; it makes childbirth dangerous for the mother (not to mention the baby). It's pretty clear that if we could think as well with a more efficient design accessible to evolution, there would be a strong pressure in that direction.

That's not to say that we need to simulate the brain at the neuron level to get AI; in fact we can very likely get away with 86 million, as opposed to billion, MIPS. Even so, the parts of the problem on which the pioneers had their then-impressive successes—proving theorems and playing chess, for example—turned out to be the very lowest of the low hanging fruit, and it has been quite a tough climb up into the higher branches.



Ike Marvelous

Powder of Life

*Brittleness in Google's book-transcribing AI, from about a decade ago:
Ozma of Oz*

The title of Chapter 2 of *Ozma of Oz* is “The Marvelous Powder of Life.” The transcription algorithms employed by Google Books mostly got it right; they found and clipped out the chapter heading picture, and interpreted the printed title almost right. But the image clipper snagged just a little bit of the “T,” as you can see at the lower left corner of the picture, and then mangled its interpretation of the word “The” in the title.

The title it came up with makes no sense at all. We can tell that the algorithm did have feedback from the word level: it knew that “Ike” was much more likely to be a real word than “The,” which is most likely what the character-level nodes reported. But phrase-level feedback was missing in action, as was any internal ability to gauge the likely excesses of the picture-clipping algorithm.

The entire history of computer science has been one of learning, by painful experience, just how many errors are made by a programmer even tackling a simple, well-understood problem with well-understood techniques in a

completely controlled environment. C. A. R. (Sir Antony) Hoare, one of the pioneering British computer scientists, said in his 1980 Turing Award lecture, [\[203\]](#)

This happened just one week after our inquest on the 503 Mark II software project [a major failure]. I gave desperate warnings against the obscurity, the complexity, and overambition of the new design, but my warnings went unheeded. I conclude that there are two ways of constructing a software design: One way is to make it so simple that there are *obviously no deficiencies* and the other way is to make it so complicated that there are *no obvious deficiencies*.

The first method is far more difficult. It demands the same skill, devotion, insight, and even inspiration as the discovery of the simple physical laws which underlie the complex phenomena of nature. It also requires a willingness to accept objectives which are limited by physical, logical, and technological constraints, and to accept a compromise when conflicting objectives cannot be met. No committee will ever do this until it is too late.

(emphasis in the original.) As a computer scientist, I remember reading with painful empathy Hoare's autobiographical account of the moment he realized that he was going to spend a substantial portion of the rest of his life looking for his own programming errors. But the rest of the world, notably corporate and government bureaucracies, has yet to learn Hoare's lesson. Not even the information processing world has learned it; today's software systems are unwieldy, bug-ridden monstrosities that would make Hoare's example look simple and elegant in comparison.

The point of this exposition is not to mock the AI pioneers; indeed quite the contrary. I got into the field early enough to have met and talked with most of them in person. They were among the brightest people I've ever known. Early over-optimism to the contrary notwithstanding, they laid the groundwork for one of our greatest achievements of science and engineering—indeed, possibly the last purely human achievement of that magnitude. Fifty years is a tiny amount of time, historically, for what has been accomplished, and the project will likely be finished inside a hundred.

The point instead is this: these very smart people drastically underestimated the breadth of knowledge, the depth of understanding, the systems complexity, the degree of internal autogeny and self-regulation, and the raw processing power necessary for something we all have everyday experience with: one person's thinking. One brain. How likely is someone who thinks he can optimize the activity of a whole society—300 million, say, or 7 billion, brains—to get it right? How much more hubris will he bring to the overestimation of what he thinks he can design?

The early AI programs were written exactly the same way we write laws and regulations: sit down and write rules—in words—for everything you can think of beforehand that might happen. Give a system like that a task exactly like the one it was designed for, and it works like a charm. Give it one even a tiny bit different, and it has a tendency to do something outrageously clueless. AI researchers refer to this as “brittleness.” Hayek, quoting Adam Smith, called it the “Fatal Conceit.” He meant something more than that symbolic-AI-like bureaucracies are incompetent. The conceit is that while they are incompetent, the people who build them, like the AI pioneers, vastly overrate their capabilities. It's a Dunning-Kruger effect on a vast social scale.

Hence, a Witch!

From roughly 900 to 1300 AD, Europe experienced a climate optimum known as the Medieval Warm Period. Then from roughly 1300 to 1850, temperatures dropped so much that the period is known as the Little Ice Age. [204] Winters were longer, growing seasons were shorter, droughts increased, and crops failed. Starvation and disease became more common as a result.

Who to blame for these disasters? One of the major upheavals of the period was the Reformation, when the people lost faith in the established Church. Another was to accuse anyone who looked a bit strange, of witchcraft. The wave of witch trials, tortures, and burnings that swept Europe coincided with the period that the climate was getting worse. Some 50,000 people were executed—being burned at the stake is a particularly excruciating form of torture—over the period, most of them women. Some scholars have put it up to the Reformation and thus the breakdown of authority. [205] But then what caused the Reformation? It makes more sense to ascribe both to the same real physical cause.

As the LIA bottomed out and the climate began to improve, the witch hysteria abated and by 1700 or so had largely burned itself out. There was of course no causal connection between witches and climate. But imagine that there had been—and that it was the opposite of what was firmly believed by the people and the authorities. That is, imagine that burning witches somehow actually caused the bad weather. There would have been a particularly nasty feedback loop, burnings causing bad weather causing more burnings causing worse weather.

Something like that actually happened in more recent times: the Xhosa. Of course the difference from the European witch-burnings is that in the case of the Xhosa, there really was a causal connection—in the opposite direction that people believed. Kill your cattle and burn your plows, and you get less food and more dependence on the European interlopers. It was the classic setup for a feedback-loop death spiral. This is the worst form of Failure of Feedback, not only the lack of a stabilizing negative feedback loop but the presence of a pernicious, runaway-inducing, positive one.

These are unfortunately not rare in human affairs; all it takes is blaming the wrong thing for your troubles. We self-deceiving humans are all too good at that.

Something of the same thing seems to have happened, in much milder form of course, with the Great Stagnation. We have had Luddites since Ned Ludd, but when the anti-technological grinch began to get traction in the 1960s, our society had become bureaucratized enough that there was a palpable ill effect on the economy as a whole. People are generally terrible at unraveling complex chains of causality through the economy, and will typically blame whomever is most closely associated in the public mind with any problem. They blame aeronautical engineers, not regulators, for the lack of flying cars. They blame oil companies, not price controls and drilling bans, for an energy crisis. And at least to some extent they blamed technology, not the fact that it was being suppressed, for the economic malaise of the Seventies. That in turn called for more regulation, which suppressed more technology, in a runaway feedback loop.

The prophets of doom are ever with us. There is a long history of millennial cults, so much so that the deranged doomster is a humorous stereotype. But they have staying power because in our public intellectual circles there appears to be no feedback that punishes wrong predictions. It doesn't seem to matter that they keep predicting catastrophes that don't happen; that somehow seems to give them more rather than less credibility with their followers. A classic example is *Population Bomb* author Paul Ehrlich, who lost a famous wager about resource depletion with Julian Simon:

All of [Ehrlich's] grim predictions had been decisively overturned by events. Ehrlich was wrong about higher natural resource prices, about "famines of unbelievable proportions" occurring by 1975, about "hundreds of millions of people starving to death" in the 1970s and '80s, about the world "entering a genuine age of scarcity." In 1990, for his having promoted "greater public understanding of environmental problems," Ehrlich received a MacArthur Foundation Genius Award." [Simon] always found it somewhat peculiar that neither the Science piece nor his public wager with Ehrlich nor anything else that he did, said, or wrote seemed to make much of a dent on the world at large. For some reason he could never comprehend, people were inclined to

believe the very worst about anything and everything; they were immune to contrary evidence just as if they'd been medically vaccinated against the force of fact. Furthermore, there seemed to be a bizarre reverse-Cassandra effect operating in the universe: whereas the mythical Cassandra spoke the awful truth and was not believed, these days “experts” spoke awful falsehoods, and they were believed. Repeatedly being wrong actually seemed to be an advantage, conferring some sort of puzzling magic glow upon the speaker. [\[206\]](#)

By 2015, even the *New York Times* managed to notice that Ehrlich's relentless doomsaying had been nowhere close to accurate: [\[207\]](#)

No one was more influential—or more terrifying, some would say—than Paul R. Ehrlich, a Stanford University biologist. His 1968 book, “The Population Bomb,” ... forecast that hundreds of millions would starve to death in the 1970s, that 65 million of them would be Americans, that crowded India was essentially doomed, that odds were fair “England will not exist in the year 2000.” Dr. Ehrlich was so sure of himself that he warned in 1970 that “sometime in the next 15 years, the end will come.” By “the end,” he meant “an utter breakdown of the capacity of the planet to support humanity.”

As you may have noticed, England is still with us. So is India. Hundreds of millions did not die of starvation in the '70s. ...

And let us add that all life in the oceans did not die before 1979 because of pesticide use, as Ehrlich predicted in 1969. Four billion people did not perish in a “Great Die-off” between 1980 and 1989, as Erlich assured readers of the 1970 Earth Day edition of *The Progressive*. 200,000 people did not die in 1973 of “smog disasters” in New York and Los Angeles. Nine-tenths of the original tropical rainforests were not removed before 2005. Industrial production has not sunk to zero, nor is civilization a distant memory, as *Limits to Growth* told us it would be by now. Earth's temperature did not rise “several degrees” before the year 2000, threatening “all life,” as we were assured it would in 1986 by PBS. Nor is Manhattan's West Side Highway underwater, as we were assured by James Hansen in 1988 that it would be. That would have implied a sea-level rise of 10 feet;

actual sea level rise since then has been 3 inches. Hanson also claimed that by now the planet would have warmed 3 degrees C; as of this writing it is 0.1 degrees warmer than when he said that. The polar ice cap was not “completely gone” by the summer of 2014, as Al Gore warned us it would be in his Nobel Peace Prize speech in 2007.

Note that by training Ehrlich was an entomologist whose PhD was on the classification of butterflies; Simon was an economist. Yet Ehrlich’s Wikipedia page lists 18 major prizes that he received, including the MacArthur mentioned and Fellow of the Royal Society. Being right did Simon no good at all: a complete Failure of Feedback. The result is that academia (and thus the popular-science press) is awash in deep-seated pre-scientific superstitions with tremendous memetic staying power—because in the absence of running up against reality on a battlefield, ideas are evolutionarily selected for intuitive appeal rather than for objective truth. Ehrlich and his colleagues seriously believed that they were taking candy from a baby with the Simon bet, but the fact was that Simon, originally sharing the same intuitions, had made an unexpected discovery while doing his economic analysis: in practice, in general, on average, and over the long run, resources such as minerals act just like other goods. Raise the price, and you’ll get more of them. In the long run, they will obey the same learning curve as anything else, and the price will go down. Simon’s insight was that the key element in any resource is not rare dirt but know-how, and ingenuity is capable of adding to that indefinitely. Anyone who grasps the capabilities of a mature nanotech should have no trouble understanding this. The big puzzle is why the ivory tower, whose business is nominally ingenuity and the production and transmission of knowledge, is so hostile to this interpretation. Perhaps we can only remember that the memetic jungle of academia and intellectual discourse is a strongly evolutionary ecosystem. Any evolutionary ecosystem always produces both predators and parasites, in the war of each idea against all. The elephants in the brain are fittest in the environment of academic adaptation; and the life of truth, solitary, poor, nasty, brutish ... and short.

More than any other time in history, mankind faces a crossroads. One path leads to despair and utter hopelessness. The other, to total extinction. Let us pray we have the wisdom to choose correctly.

—Woody Allen

Intellectuals hate progress. Intellectuals who call themselves “progressive” really hate progress.

—Stephen Pinker

Only in academia and government, where nobody faces consequences for failure, do you find people who are stupid enough to believe they know what is going to happen.

—Eric Worrall

When investors and fund managers are right more often than they are wrong, they are rewarded—handsomely. When they are wrong more often than they are right, they lose money or clients, usually both. The world of public intellectuals is different. Using their academic credibility to pontificate about the future, professor-pundits can be wrong again and again without losing money or their tenured jobs. Many distinguished and lucrative careers have been based on just such a pattern of unpunished error.

—Niall Ferguson

Pollution

In the world of Eloi Agonistes, a new memetic organism evolved. There is certainly a feedback to the horror story industry, but as we have seen it has nothing to do with whether the stories are proved right or wrong in reality. Pundits and organizations profited greatly, both in money but perhaps more importantly in prestige; and this is the feedback that counted. But the scare industry is completely unregulated, and its profits come at the cost of a great social externality: the pollution of knowledge with dire falsehoods. The classic example is the discovery, after Three Mile Island, that 66% of Americans had been sold the malicious but completely fallacious story that nuclear power plants could explode like atom bombs. A more recent example is the revelation [\[208\]](#) that 39% of Americans believe

that global warming is likely to cause the extinction of the human race. (The actual published estimates for the IPCC's worst case scenario, RCP8.5, are for a reduction in GDP of between 1% and 3%. [\[209\]](#) And RCP8.5 assumes that all the world's power will still come from burning coal in 2100.) Consider, if you will, a chemical company which, by slovenly practices and lack of concern, leaks poisonous by-products into the community's water supply. Now consider the scare industry, whose main product consists of intentionally poisoning children's minds. Aesop's boy who cried "Wolf!" discovered that he could, briefly, become the most important person in the village, with everyone paying attention to him, dropping what they were doing, responding to his call. Ultimately, of course, he lost all credibility and was devoured by the real wolf when it came. In our world, the scare industry has managed to become embedded with academia, science, and government. Ultimately, this appears to be in the process of weakening and discrediting these vital sectors of our society. It surely contributes to what Tocqueville described as "the singular melancholy that the inhabitants of democratic lands often display amid their abundance, and the disgust with life that sometimes seizes them in the midst of an easy and tranquil existence."

——Bottom Line——

Machine learning is the science of credit assignment.

—Jürgen Schmidhuber

On January 28, 1986, I was in an airliner heading home from my grandfather's funeral in Florida. The captain came on the public address system to impart a bit of amusing trivia: the outside air temperature was ninety degrees below zero, while we were still over Florida. The jet stream had wandered down from higher latitudes, lowering temperatures well below normal, on the ground as well as in the air.

I remember that bit of trivia over three decades later because of its then-unknown implications: the same cold wave had stiffened the material of the O-rings in the solid rocket boosters of the space shuttle Challenger, causing a leak of combustion gases which resulted in the break-up of the vehicle.

But nobody knew that at the time; it took the Rogers Commission six months to finish its report, with Richard Feynman famously demonstrating the cold-caused lack of flexibility with a glass of ice water.

Well, not exactly nobody knew: it turns out that Allan McDonald, director of the Solid Rocket Motor Project at Morton Thiokol, had warned of the problem and in fact had refused to sign off on the launch. He was rewarded for this exercise of responsible foresight by being removed from his position and demoted. Feynman himself had to threaten to resign from the commission and remove his name from the report unless it included his observations of the enormous communications gap between NASA engineers and management.

The Dilbertization of NASA, more painfully obvious in later years, was hardly limited to NASA itself. In fact, NASA, especially in the Sixties, probably represents the best-case scenario for such a designed bureaucracy: a collection of the nation's brightest people, with a common goal and vision, committed to a concrete, well-specified task. One of the engineers, remembering decades later the way it had been, described the feeling, "There wasn't actually a sign saying *Waste Anything but Time!*, but it felt

like it.” [\[210\]](#) Like the Greatest Generation in the Fifties corporate state, there was a pronounced “same boat” spirit.

But even in the best human-designed bureaucracies, the primary function of the system will ultimately become insulating decision makers from accountability and feedback. The simple and obvious reason is that people don’t like to be held accountable, and if allowed to design the systems they work in as they like, will put in plenty of insulation. And once that happens, cynicism sets in and the “same boat” spirit evaporates.

The highly predictable result is that bureaucracies are very poor at learning. The reason “good old-fashioned” symbolic AI systems didn’t work reliably is that they were like bureaucracy; and the reason that bureaucracies don’t work is that they are like good old-fashioned symbolic AI. The “cost disease” that infects so many of our basic services, from education to infrastructure to medicine, reached the epidemic stage at the same time as the burgeoning bureaucratic and regulatory runaway of the Great Strangulation. The causes of it have proven quite resistant to conventional analysis, but there is one thread running through all the social pathologies: Failure of Feedback. Systems are designed and decisions made by people with no incentives for quality or efficiency; regulations are promulgated by coalitions of Baptists and Bootleggers. And because it is embedded in the political system, the sector that operates this way has been growing like a cancer, immune to the feedbacks and accountability that regulate growth in the rest of the economy.

The early, brittle, AI programs were very bureaucracy-like. In fact, all programs of the standard sequential imperative form are very bureaucracy-like. Computer programs are the least sentient technology we’ve ever invented. You can fly an airplane by the seat of your pants, partly by virtue of the fact that all the control pressures through the stick or yoke go both ways; you can feel how hard the ailerons, rudder, and so forth are biting the air, and they of course respond proportionally as you push back on the stick. You can’t push back against a program, or bureaucracy, that simply cannot listen.

The latest horror-industry trope is right out of science fiction: it is Asimov’s “Frankenstein Complex.” People are trying to gin up worries that an AI will become more intelligent than people and thus be able to take over the world, with visions of *Terminator* dancing through their heads. Perhaps they

should instead worry about what we have already done: build a huge, impenetrably opaque *very stupid* AI in the form of the administrative state, and bow down to it and serve it as if it were some god.

The difference between bureaucracy and artificial intelligence is that computer science is, perhaps surprisingly, really a science: you can do hard, falsifying tests of your hypotheses in controlled experiments ... if you care to. The people in AI have been doing this, willy-nilly, for half a century. We have been trying to build a machine as smart as a person, and when instead what you built turns out to be a clueless imbecile, it's time to get back to the drawing board. And thus, slowly and painfully, reinventing cybernetics, we learn to put feedback into our systems, down to the very lowest levels. And because AI is at least in part a science—a “science of the artificial” in Herbert Simon's phrase—there is enough feedback in the field as a whole to allow for escape from Machiavelli Effect traps such as the one which suppressed neural networks for a while.

As we approach the ability to create working artificial intelligence, we are beginning to write programs that do learn: deep-learning neural networks, for example. The way these work is that the mechanism of the program is spread in a distributed way across many simplified computational units. The key is that the function of each unit is “differentiable:” if you specify which way the output was wrong from what it should have been, it is possible to calculate which way each of the inputs should have been different, propagating the error backward through the network. Now each unit has a purely local view of what it's doing wrong, and it has a much easier task to optimize than the overall learning problem as a whole.

The economy, it turns out, does much the same thing. In machine learning theory terms, the market machine does “credit assignment” by “back-propagation” of explicit credit tokens—money—as a counterflow to the actual goods and services being produced. This reduces the problem of overall optimization to the one of each unit maximizing the net local money flow. That makes the overall economy an effective learning machine, just as back-propagation does a neural network. As Hayek put it in his Nobel acceptance address, “We are only beginning to understand on how subtle a communication system the functioning of an advanced industrial society is based—a communications system which we call the market and which

turns out to be a more efficient mechanism for digesting dispersed information than any that man has deliberately designed.”

The other beneficial aspect of the market mechanism corresponds, perhaps surprisingly, to another of the leading AI techniques for preventing brittleness: artificial evolution. In the biological world, red in tooth and claw, the process is covered by a veil of niceness in the phrase “survival of the fittest.” What really makes the difference is the death of the unfit. In the market, the feedback mechanism forces firms into bankruptcy when they consume more than they produce. An AI, if operated according to these principles, can let its incorrect ideas die in its stead.

Up until the Sixties, the American culture and economy actually worked this way, by and large. It was dynamic, innovative, and growing, providing the prospect that our children would be better off than we were. But I think that the Aquarian Eloi Agonistes failed to understand how it worked, why in general the best way you can help improve the world is to make as much money—honestly, of course—as you can. You simply cannot know enough to do a better job than the distributed system that aggregates value and cost signals over the whole world. Money is a harsh mistress; it forces you to produce more value than you consume. As Milton Friedman put it, “The social responsibility of business is to increase its profits.” People chafe under the (literal) accountability it imposes. In the fervor of their crusades, the Eloi wrapped themselves in a many-colored cloak of insulation.

Again and again, when the Eloi Agonistes attacked an apparent problem, they brought emotion and self-deception rather than understanding. In the classic case of the energy crisis, for example, when energy in the form of oil becomes scarce, the price rises. This is a signal and incentive for several things: oil users economize and cut back on less valuable uses. People try to move oil from places where it is plentiful (and cheap) to places where it is scarce (and dear). Others begin to spend more resources and effort on finding new supplies or inventing substitutes. These are all exactly the things any sensible governor would do in the case of a shortage. But instead, cynical pols (notably Nixon) said, “Oh, horrible, the price of oil is too high,” and instituted price controls, anesthetizing the pain of overuse, choking the incentive to create new supplies, and causing an energy crisis where none existed before.

It may well be possible to design a better machine for social and economic control than the natural marketplace. But that will not be done by failing to understand how it works, or by adopting the simplistic, feedback-free methods of 1960s AI programs. And if ever it is done, it will be engineers, not politicians, who do it.

[It is natural] to seek for such evidence and appearances as are in the favour of our desires, and to disregard those which oppose them. ... We receive as friendly that which agrees with [us], we resist with dislike that which opposes us; whereas the very reverse is required by every dictate of common sense.

—Michael Faraday

It is hard to imagine a more stupid or more dangerous way of making decisions than by putting those decisions in the hands of people who pay no price for being wrong.

—Thomas Sowell

Quis custodiet ipsos custodes?

—Juvenal, quoted by Heinlein in *Space Cadet*

16 Here We Stand

For ages man lived in a world where he was a slave to the elements. His own achievements were by comparison crude and immature; his every living moment was subject to the blind caprices of fate. Not unnaturally, he dreamt of greater things. At first his achievements were limited to dreams, and to dreams only. ... It was not until man found himself capable of transforming dreams into prophesy that he wrote science fiction. ... The only difference between the science fiction fan of today and the Homer of yesteryear is that the fan of today knows that there is a sufficiently large kernel of truth in his dreams to make them possible of realization—that the fantastic fiction of today may well become the fact of tomorrow.

—Sam Moskowitz, *The Immortal Storm*

The Golden Age SF writers understood the technology for things like flying cars reasonably well. They understood the potential of nuclear power fairly well. The one thing that got really over-promised from a technological standpoint was fusion—they were about 50 years optimistic, at a guess. And even then their problem seems to have been listening too closely to the accredited scientific experts of the day.

Ironically, the reasons for mispredictions were opposite for flying cars and for space travel. In the former case, a technology that would have developed normally over the century was hobbled by the Depression and WWII, hounded by a nearly inexplicable government legal effort in the postwar era, stifled by regulation thereafter, and then essentially extinguished by liability lawyers.

On the other hand, rockets and space flight were highly funded by governments, for military reasons and as programs for national prestige. By the 60s, some writers (notably Clarke) were beginning to mistake that for sustainable progress, producing an overly optimistic view of things like planetary colonization in our lifetimes. The only major writer who was close to the mark was Heinlein, who predicted a takeover of the US

government and ruling class by a religion hostile to technology, and a hiatus in space travel.

Nuclear power—the abortive Atomic Age—was a fascinating case of both phenomena. During WWII, the government spent an enormous amount of money and effort developing nuclear weapons. This gave pundits, including SF writers, the belief that we had solved the mysteries of the atom and had a great new energy source available. In fact, the huge investment in the atomic bomb—the Manhattan project built more industrial plant than the entire American automotive industry—was a dead loss economically.

The Manhattan project cost roughly \$2 billion in nominal dollars. The only single project that cost more was the development of the B-29 fleet, which cost \$3 billion. The investment and technological experience in the B-29 did pay off economically. The post-war years benefited from large, pressurized, high-altitude airliners, and their continued development was commercially sustainable. By contrast, the military restrictions on anything nuclear hobbled private experimentation and development. It took nearly two decades from the first super-secret “atomic piles” to an economically useful nuclear power sector. Then within another couple of decades, regulation petrified the industry.

On the other hand, during the 70s and 80s, computing went through a phase change, from bureaucratic computing centers in corporations and universities to a multitude of smaller, private, unregulated machines.

Combined with the growth of the Internet in the 80s and 90s, this kept information technology essentially on the track the technological optimists predicted. Asimov and Clarke got the state of applications ranging from robots to planetary libraries more or less right. The experience of ordering something online (*i.e.* with video pictures on a home console) and having it delivered today is flabbergastingly close to what Nowlan predicted in 1927 and Heinlein gave a more detailed picture of in 1938. The main difference is that physical delivery takes longer.

The rest of technology, particularly anything high-energy, remains in the computer center era, with supplicants looking in through glass walls, and kneeling at the I/O counter to offer their card decks for runs and to be blessed with their output. Airline travel is exhibit A.

In the background, scientific knowledge has kept advancing, Great Stagnation to the contrary notwithstanding. The rate of technological

progress in areas without opposition or strangulation, such as computer technology, has been tremendous. Over the period that commentators note as having had little life-altering technological advance, basic science has discovered planets around other stars, and indeed increased the number of known bodies in our own solar system by a factor of 1000, including a second moon of the Earth. We have solved the molecular mechanisms of life itself, both working out the molecular shape and function of the genome and then reading it; and mapped the human brain, producing remarkably detailed wiring diagrams. We have built giant underground neutrino telescopes and measured the 450,000,000,000 neutrinos per square inch per second that sleet through our bodies direct from the nuclear processes at the center of the sun. We've detected a flash of gravitational radiation from a stellar system collapse so violent that three solar masses of matter were converted into energy in the form of waves in the fabric of spacetime itself. A substantial part of the expected but unattained technological advances were not mispredictions of technology. They were instead misplaced faith in the vitality and dynamism of our culture, and of the wisdom and indeed basic competence of our information providers and systems of governance. We poured increasing torrents of money into the ivory tower and other virtue signalling, and it increasingly took our best and our brightest away from improving our lives.

Let us have a guess at where our various technologies might be now if we had kept the culture of the Fifties, or something like it.

- Cybernetics and Artificial Intelligence. The implosion in cybernetics had already happened, but it wasn't apparent from the outside. The ensuing low-level war between AI and cybernetics probably set the overall field back some, but the limiting factor was probably raw processing power. Thus Asimov's prediction seems to have come out more or less right. Even such a wild-eyed adventurer as your author hesitates to speculate on whether a healthy cybernetics might have improved governance over the period.
- Nanotech. It had been understood since 1960 how to go about developing it, and since the 1980s just how powerful a technology it is likely to be. On the other hand, the Machiavelli Effect backlash didn't happen until the later Nineties. I have estimated elsewhere that it set

nanotech back a decade; I'll stick with that. It seems likely that we might well be using ammonia fuel cells by now, without the backlash, but cell repair machines would still be in our future.

- Biotech. Religious objections and crusades, in which I include both fundamentalist Christian and fundamentalist Green, have hampered the field significantly, but I don't know enough about it to make even a handwaving guess at how much.
- Nuclear power. This is probably the greatest failure of achievement compared to what we might reasonably have expected. Essentially all our electric power should be nuclear today. Instead we got massive campaigns of fear and misinformation; a complete failure of the educational establishment; typical kitten-in-a-tree paralysis from the regulatory bureaucracy; a factor of seven increase in the cost of nuclear power; and 500 billion more tons of CO_2 in the atmosphere.
- Cold fusion. Here the Machiavelli Effect backlash was unusually strong and swift. Of course, we might very well have funded cold fusion at a billion a year since 1989 and gotten nothing. A fair amount of progress has been made on shoestrings since then, however. I would guess that without the backlash we might have gotten the same amount of nothing we have now, by the turn of the century. Where it could have gone from there is anybody's guess.
- Flying cars. Had the 1980s liability crash not happened, there would now be a 30-40,000 airplane per year business, going by the previous trend line—and that would be within the existing regulatory framework. Note that the Robinson R44 helicopter is the best-selling single model of any aircraft of any type today. Technologically, we could easily have flying cars now. It would have required a complete overhaul of the air traffic control system, however.
- Multi-level cities, sea cities, domed cities, aerostat cities: Cities with “moving ways,” multi-level streets, and suchlike infrastructure are of course possible with current technology. Over the past 50 years, the planning of cities has been taken over by anti-technological ideologues, and their management by political machines interested far more in retaining their grasp on power than in the welfare of their citizens. We could have done much, much better.

- Space travel. Chemically fuelled space travel is on the verge of commercial feasibility now. We could have had a continued government-funded exploratory space program throughout the past several decades that would have given us a leg up in experience. Nuclear-powered spacecraft, notably of the Orion type, could have given us an orders-of-magnitude better launch capability, and a not particularly aggressive development program would have produced a fairly mature technology by now.

——Bottom Line——

Imagine that the best and brightest of my classmates had spent their time studying instead of protesting, and gone on to become engineers instead of activists, regulators, and lawyers. Imagine that education, health care, and public works had not been overcome by the cost disease. Imagine that the private aircraft industry had grown instead of being destroyed; that the Henry Adams Curve had not flatlined; that technology had continued to develop, and life to improve, at the rate it had done in the previous 50 years. Purely from a technological standpoint, what would life be like now for the typical American?

To begin with, the average American would be about 4 times as wealthy; call it a median \$200,000 family income as opposed to today's \$50,000. Approximately the top 5% of families now can afford two homes; the top 50% would have been in the same bracket. This is essentially the demographic which could, if they wished, own an airplane.

The makeup of the "products" that constitute the GDP would be different, and would run more to actual machines and less to expensive paper-pushing. (The size of the financial sector has doubled as a fraction of the GDP since 1980; it's bigger than the energy sector. Both the educational and medical sectors today rake in ten times as much, in relative terms, as they do in countries with similar results.) There would have been more experience with things high-power and high-tech, and so we would be much farther down the learning curve with, for example, turbine aero engines. It's not outrageously over-optimistic to guess that a non-trivial fraction of families could have owned a helicopter. Given that we are seeing the emergence of electric ducted fan VTOLs in the real world as I write

(e.g., the Lilium), it's a pretty easy bet they would be around in our alternative scenario. They, and multicopters like the Volocopter, would be powered by turbine-generators, and thus have ranges measured in hours instead of the tens of minutes of the current battery-powered prototypes. If transport costs had, in fact, kept tumbling, particularly in terms of time, we would have seen a continuation of the great push out into the exurbs. The difference is that a flight-based regime of expansion not only merely expands the sphere of influence of an urban center; it makes multiple urban centers *and all the space in between* available to the rural dweller. And that in turn means that it becomes viable to put a business just about anywhere. Inasmuch as the progress to robots has come about as fast as could be expected, we wouldn't expect the state of the art to be enormously beyond today's. On the other hand, it is not perhaps widely understood just how good our manufacturing and other automation actually is now. The difference would be the amount of it that would be affordable to the private consumer; you would see work being done with powered exoskeletons or tele-operated waldos, for example. So your mountainside home, complete with rooftop landing pad, is built in half the time by half the people it would take now.

A big watershed would come when it became reasonably economical to build and occupy such a home without building a road or physical utility connections. UPS drops by every day, in a big brown helicopter, and your own family VTOL takes care of most simple transportation needs. Telecom is easy, we've essentially got that today. But what about power?

There are many options. We are assuming a vigorous, non-collapsed nuclear power technology, several generations on from current dinosaurs. NASA's 10 kW kiloPower reactor, currently under development for use on Mars, and about the size of a telephone booth, would be perfect except for cost and proliferation issues. The most straightforward alternative would be isotopic batteries (direct electric, not thermal), as foreseen by Asimov. If you don't trust Asimov's (and my) technological intuition that direct conversion would be economic now if there had been 50 years' research and innovation in the field, note that the technology of thermal conversion hasn't stood still since the Eisenhower administration either.

Even if instead we had built a cell system with small modular reactors of a more-or-less conventional design every few miles, or a solar power satellite

system, we could transmit power to the house. Cover the roof with photovoltaics for solar power, but get it out in the form of fuel which you then feed into fuel cells. Both conversion steps are seeing hints of happening in the lab today, and would probably just be becoming practical with a non-stagnated nanotech. The technological possibilities are endless; it's a question of what's more economical. And all that in turn merely gets balanced against the cost of running power lines, or regular propane deliveries.

In any case we can fairly confidently guess that the diaspora from the cities would have continued rather than reversing. This would include the sea, the mountains, and other areas on the Earth's surface. There would be substantially more space travel and exploration, but not as yet substantial colonization—there's an enormous amount of room here on Earth that is vastly underutilized as yet. A major push to live in space will not happen until we have mature, full-fledged nanotech. In a pro-technology alternative present, we would be seeing the very earliest real nanotech applications right about now, essentially the same stage that personal computing was in 1980.

If flying cars had been developed in the later 20th century, they would almost certainly would have used turbines. Today there seems to be a Cambrian explosion in proposed flying car types, and many of them are battery/electric. At my best reading of the technical literature, the headroom for batteries in known chemistries is about a factor of 8 in energy density and maybe cutting the price in half. This is certainly good enough for ground cars and even fixed-wing airplanes, but not VTOL. On the other hand, fuel cells appear to be a fairly low-hanging fruit for early nanotech, and could be a drop-in replacement for aircraft which had been developed using batteries. So I am inclined to view the current electric flying-car enthusiasm as being more sustainable than it might otherwise be.

There are many new technologies that may appear in the coming century, some more anticipated than others. How many of them will manage to recreate the miracle of the Industrial Revolution, and improve the life of the ordinary person by an order of magnitude? We shall see.



Indeed, law and police, trade and industry, have done far more than people of romantic dispositions will readily admit, to develop in our minds a sense of the wilder beauties of nature. A traveller must be freed from all apprehension of being murdered or starved before he can be charmed by the bold outlines and rich tints of the hills. He is not likely to be thrown into ecstasies by the abruptness of a precipice from which he is in imminent danger of falling two thousand feet perpendicular; by the boiling waves of a torrent which suddenly whirls away his baggage and forces him to run for his life; by the gloomy grandeur of a pass where he finds a corpse which marauders have just stripped and mangled; or by the screams of those eagles whose next meal may probably be on his own eyes. . . .

It was not till roads had been cut out of the rocks, till bridges had been flung over the courses of the rivulets, till inns had succeeded to dens of robbers . . . that strangers could be enchanted by the blue dimples of lakes and by the rainbows which overhung the waterfalls, and could derive a solemn pleasure even from the clouds and tempests which lowered on the mountain tops.

—Macaulay, *History of England*

Part III. Profiles of the Future

17 Tom Swift and his Flying Car

If a man can write a better book, preach a better sermon, or make a better mousetrap, than his neighbor, though he build his house in the woods, the world will make a beaten path to his door.

—Ralph Waldo Emerson

Every city in the United States will have a landing-field and hangars for airplanes, as well as mechanics to care for them. Whether this is to be a private or public enterprise lies in the hands of the people handling such things. Much could be said for either type of establishment. The thing must come; it is as logical as one, two, three. There are some, perhaps, who remember the roars of derision which went up when the first automobile garage was established in their town. Such a thing was visionary—there would never be enough machines to make it pay!

—Sweetser and Lamont, *Opportunities in Aviation* (1920)

Aeronautical innovations

There have been, over the course of the 20th century, a number of aeronautical innovations that could contribute to the design of a flying car.

Electric Jets, I



The Schübel DS-215-DIA HST can produce 56 lbs thrust from 15.6 kW electric power (21 HP) in an 8-inch package. [\[211\]](#) It falls right along the thrust / area curve in Chapter 13 at 150 pounds per square foot and 2.5 pounds per horsepower.

In the model aircraft world, “electric jet” means a ducted fan powered by an electric motor. Modern rare-earth magnets and other innovations have made possible electric motors at the same power-to-weight ratios as turbines, even at model sizes. Full-sized superconducting ones could have better ratios yet. Electric motors would allow considerable optimization of the placement and control of thrusters, perhaps enough to have separate lift and cruise motors.

The major problem with electric motors is providing the electricity. Batteries are horrible from a weight perspective. When my plane is filled up, the avgas weighs 360 pounds. The same usable energy in lithium-ion batteries would weigh about three tons (and cost \$170,000, without charging circuitry). [\[212\]](#) I literally could not get off the ground.

Furthermore lithium ion batteries are notoriously prone to spontaneous combustion. These were the batteries whose problems famously grounded the Boeing 787 Dreamliner fleet just as it was getting started.

One apparent possibility with batteries is to use them for short, high-power phases of flight, *i.e.* takeoff, and use a smaller engine to power the aircraft in cruise and recharge the batteries. The Terrafugia TF-X design for a VTOL flying car appears to use this approach, for example. For my money, this is not a good idea. Takeoff time in a VTOL is the one phase of flight where power failure is most deadly, and any power system is being driven the hardest. Having that power system consist of batteries subject to catastrophic failure is asking for trouble.

A possible workaround is to have say 100 small lift fans each with its own separate battery; you could afford a few going up in smoke at just the worst time. But even if you can manage 100 square feet of thruster area—a car's footprint—you will need about about 650 pounds of LiPo batteries for five minutes of 4000 pound thrust.

There is a completely inescapable problem with chemical batteries which gets worse as the batteries get better. If you crash in a gasoline-powered plane, the tanks may rupture, the fuel leak, mix with air, and catch fire. That's bad enough. But suppose battery technology had improved to the point that the battery had the energy density of the gasoline. Rupture one of those and the energy is all right there, no spilling and mixing necessary. It will be very difficult to make such a battery that wouldn't simply explode under such circumstances, with an energy per weight about ten times that of TNT.

One alternative is to use fuel cells; like batteries, these have been steadily improving since the Sixties. At the bleeding edge today, custom-built ultralight cell stacks (at \$10,000 per kilowatt) can produce a kilowatt per kilogram; this is essentially piston engine power density. The engine in my plane weighs about 250 pounds; the equivalent in fuel cells would be about 300. This is good enough for conventional airplanes (or even helicopters) but not compact VTOLs. Their main problem is that they use pure hydrogen, which is remarkably difficult to store and handle. Hydrogen infiltrates metals, causing embrittlement and making seals problematic. It's also extremely light, requiring huge containers for small amounts. One

possible solution is to use ammonia— NH_3 . Use the hydrogen and release the nitrogen back into the air, of which it is already the major component. Liquid ammonia contains more hydrogen per gallon than liquid hydrogen does! The separation step is still a little beyond current technology, though. But, I would guess, fairly close, and falling-down simple for nanotech. The best technological approach at the moment is an optimized turbine/generator. Surprisingly enough these can be bought off the shelf—they are used as APUs (auxiliary power units) in airliners. You can have a turbine-generator plus electric fan motors for less than the weight of a direct-coupled piston engine. The reason to do so would be that you can have many small fans instead of one big one, which can be tailored to the airflow around the aircraft and thus be more efficient. It remains to be seen whether this theoretical advantage can be reduced to practice.

Electric Jets, II

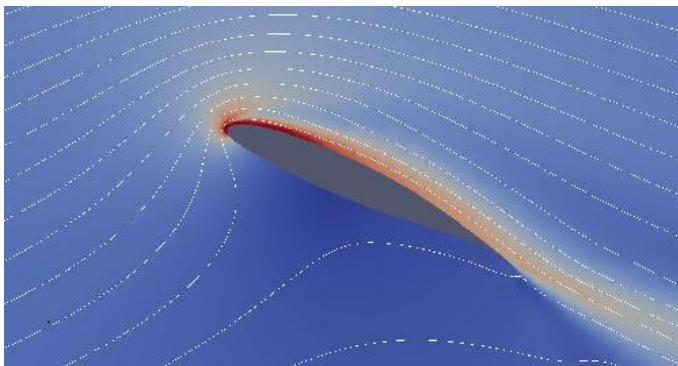
Suppose there were a different way to push air than by swinging blades through it. It might be possible to apply a small force to a large quantity of rapidly moving air without the inefficiency incurred with a fan. It turns out that such a thruster exists, if it can be engineered into useful form. It works by spraying electric charge into the air, creating ions, and then subjecting the charged air to an electric field which exerts a force on it. Such “ionic fans” have been laboratory curiosities and science fair projects for decades. Recently Barrett and Masuyama at MIT did what may have been the first rigorous evaluation of ionic thrust as a propulsion method. [\[213\]](#) Their results were surprising: they found that an ionic thruster could produce over a hundred newtons of thrust per kilowatt. For comparison, the e-jets above use about 6.25 kW per 100 newtons. Your 3000-pound car could be lifted VTOL with a 180 horsepower motor, and cruise with only 20 horsepower. Ionic thrust is far from ready for prime time, however. It involves spraying charge into the passing air from bare conductors at tens of thousands of volts. Failure modes could be spectacular. Imagine what happens when it rains! Furthermore, although the power efficiency is high, it isn’t clear whether the weight of the high-voltage power supplies can be brought down to a viable range, or how much air must be handled to create a useful

amount of thrust. Even so, there appears to be plenty of headroom in the physics for future engineers to work with.

Powered Wings

A related aeronautical feature that would be of considerable use is circulation control. This involves sending sheets of high-pressure air out of slim slots at selected spots on the wing. It can significantly improve lift-to-drag ratios, give the effect of high-lift devices with no (external) moving parts, and improve the effective aspect ratio of a wing. The no-moving-parts aspect would be particularly valuable for telescoping or folding wings. A wing with ducts and slots that were merely part of its shape could be made much lighter than one with hinges, flaps, linear actuators, and all the other panoply of current-day high-lift devices.

Circulation control, and its earlier version known as “blown flaps”, has been tested and experimented with by NASA and various aeronautical engineering departments since the 1970s, and is a continuing area of active research. Some recent work by Mark Moore of NASA Langley has centered on the novel use of circulation control in a propeller duct. The issue is that a different configuration for the duct is desirable for low-speed, high-thrust regimes such as liftoff, and high-speed, low-thrust regimes for cruising. A proper application of circulation control might let the same duct serve both purposes efficiently.



A blown wing at high angle of attack. Color is air velocity, red fast, blue slow.

One variant of circulation control is seen in this computational experiment by the author. [\[214\]](#) It involves placing a one-millimeter blowing slot on the leading edge of a wing section, at what would be the stagnation point in level cruise. Color indicates airstream velocity; in this particular experiment, the jet coming out of the slot is about Mach 1.2. The angle of attack can be twice the stall angle for an unblown wing, and the indicated lift coefficient can be over 11. This 2-D simulation would certainly not translate into real figures for a finite-length wing, but does give some indication of the kind of performance improvement that might be available. A competent aeronautics engineer (not your author!) could surely improve the design considerably. Actual blown wing designs in practice get lift coefficients in the range of 5, but don't use as much power—power is cheap in simulation! (Furthermore, anything with a supersonic flow would be extremely noisy in real life.) The bottom line, however, is that blowing the jet over the wing multiplies the lift of the jet by a factor of ten compared to blowing it straight down for direct reaction lift.

Your Flying Car

Inventor (n): A person who makes an ingenious arrangement of wheels, levers and springs, and believes it civilization.

—Ambrose Bierce



NASA Lifting Bodies

Do we really need wings? In the 1960s, NASA conducted a series of tests of wingless aircraft called “lifting bodies” as possible designs for space re-entry vehicles. The first of the series, the M2-F1, was approximately car-sized, built of plywood over a steel frame, and could glide at 100 knots, carrying a pilot. (In many of the glide tests it was towed by a hot-rodded Pontiac.) The average car today has a ground footprint of about 100 square feet. Let’s assume that you can use modern high-tech materials (including a turbine for an engine) to make it one ton of machinery with 1000 pounds of payload (typical for a small plane). If you use all the aerodynamic tricks above, and play with the shape a bit so as to call the whole business a lifting body, it has a wing loading of 30 pounds per square foot. That is high for a small plane (Piper Cub: 6 to Beechcraft Bonanza: 25) but low for a jet (Cessna Citation: 40 to Boeing 747: 150). You would be taking off and landing at about 100 knots. Parenthetically, this is one reason cars are no longer designed to look like jets and rockets the way they were in the Fifties; on the highway, you want the aerodynamic forces pressing the car down on to the road instead of trying to make you lose contact!

You do want the aerodynamic tricks in your flying car, though. By itself the car represents a wing of such a low aspect ratio (width to length of the car,

in this case) that it's highly inefficient. At the very least you need air curtains and boundary layer control to steer and contain airflows around the sides. In fact in *Childhood's End*, Arthur C. Clarke envisioned exactly this as the technological basis of the "the ubiquitous little aircars [that] washed away the last barriers between the different tribes of mankind." As he described them,

The ordinary private aircar had no wings at all, or indeed any visible control surfaces. Even the clumsy rotor blades of the old helicopters had vanished. Yet Man had not discovered anti-gravity ... His aircars were propelled by forces which the Wright brothers would have understood. Jet reaction, used both directly and in the more subtle form of boundary layer control, drove his flyers forward and held them in the air.

There are a few differences in detail, probably, to what we might actually be able to build along those lines. It won't be a "little aircar," at least compared with a ground car (although it would be smaller than an airplane of conventional design). For one thing, it needs to be big to interact with enough air to fly. For another, it needs to be built lightly, so for use on the ground you want crumple zones instead of heavy internal guard rails and other armor in case of collisions.

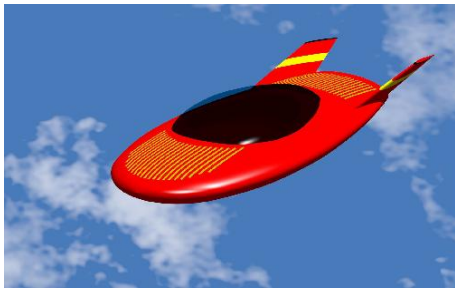
But we might want a smaller car specifically to raise the wing loading. A fully loaded 747 has a wing loading of over 150 pounds per square foot, which makes it require higher takeoff speeds and longer runways, but also makes it much less susceptible to windy weather, turbulence, and so forth. Your 3000 pound car would only need 20 square feet of wing; that's less than half the footprint of a SmartCar. Alternatively you could simply add a few tons to the weight of the full-sized car.

Another difference is that we would very likely use tailfins and canards and so forth for aerodynamic control and optimization. Clarke's engineering sensibilities—the English love of clean lines—to the contrary notwithstanding, this is an American flying car we're designing here. All that said, it seems reasonably likely we could take a car shape like this and make it take off and fly. You can throw out the power vs. speed chart,

though; all that forced air for the blown flaps and so forth doesn't come for free. Budget for a 1000-HP turbine.

Have we let ourselves in for the VTOL dilemma again? Maybe not! The two main sources of drag vary oppositely with speed. Parasitic drag, things like skin friction and turbulence caused by your passage, goes up as the square of your speed. But induced drag, which is caused by producing lift, goes down. Bigger wings mean more parasitic and less induced; smaller wings vice versa. Most airplanes are designed so that the sum of the drag terms is lowest at the intended cruising speed.

Not so our flying car. It has a high wing loading, high induced drag, but low parasitic drag (if we clean up the body a bit). So it's pre-optimized for higher speeds. All that surface blowing and air curtains become less and less necessary the faster you go. The power can be diverted back to thrust. At 400 knots, all you need from your car shape is a lift coefficient of 0.06, and that's easy, even from a very low aspect ratio wing. In real life, low aspect ratio wings are found on very fast aircraft—think of the Concorde. The NASA lifting bodies, air-dropped and rocket-powered, got up to 1000 mph. So your 1000 HP might just pay off in high speed after all. *It is a possibility.*



A mash-up of several ca. 1960 flying car designs, ranging from Gerry Anderson's Supercar to a Curtiss-Wright marketing department concept, with a nod to the lifting bodies, and of course the Jetsons.

Straight up

Can we go the whole hog, and put in down-blowing fans in the trunk and hood areas for true VTOL? In theory, there is enough thruster area for 1000 HP to lift the car. The airjeeps of the Sixties were designed along these

lines. The ones with turbines (e.g. the actual AirGeep VZ-8P) flew well, while the ones with piston engines (the Curtis/Wright Bee) made barely-working hovercraft. The question is, is there room for anything else, including the engine?

Perhaps surprisingly, the answer is probably. With the Schübeler e-jets shown above, you only need about 20 square feet of footprint (out of the 100 in a typical car) to lift 3000 pounds, i.e. 54 of the jets, drawing 850 kW. In practice you might use a few more—you could derate the jets to 10 kW, and use 64 of them at 48 pounds thrust each and a power draw of 640 kW. In either case there is plenty of footprint left over for engine, passenger compartment, wheels, and so forth. The Doak VZ-4 put 1000 HP into 50 square feet of lift fan area; a similar area in our car would leave us 50 square feet of floor space for passengers, engine, and so forth. (If that doesn't fit, you can add another 50 square feet and still have the footprint of a Ford F-150 pickup—or a 1959 Cadillac.) For an added advantage, you don't even need to use the wheels that much; with a little design foresight, all that downward airflow (and side air curtains) gives you a pretty good hovercraft. So it's even amphibious on the surface.

One difference between small planes and cars that people rarely think about is that when you park your plane on the ramp at the airport, you are well advised to tie it down. Sitting light without passengers and cargo, high off the ground for propeller clearance, it can be tossed around and wrecked by a gust of wind. No one even thinks of tying his car down. Even a car that only weighs a ton is nowhere near as likely as an airplane to catch gusts with disastrous results. Besides lacking the wings, the car is much lower to the ground than the airplane. But we can use the air cushion coming in to land instead of two-foot high landing gear, or simply retract the gear halfway for driving.

So what are you giving up? The weight and volume of your e-jets (say 300 pounds) and louver-closing arrangements for fairing at high speeds could have been useful load and cargo space. If nothing else, you could have used that for fuel; VTOL and range are hard tradeoffs. The Doak VZ-4 only had a one-hour endurance. It probably makes a two-seater out of what would have been a four-seater, had you used a mile-long runway. So you pay your money and take your choice.

You definitely get something for it, though. VTOL has some significant advantages:

- For safety,
 - You can put down almost anywhere, in a pinch
 - When you land, you are moving a lot more slowly; that means visibility is not nearly as critical as it is to a plane needing to approach at 100 knots
 - Wind shear and stalls are much less a problem
 - That 30-knot crosswind isn't a problem, since you can take off and land in any direction
- For convenience,
 - Takeoff and land virtually anywhere; latency is essentially the same as a car
 - You don't have to tie it down, or untie it to fly
 - You can fly slowly much nearer obstructions and other aircraft — significantly denser traffic patterns are possible than with airplanes
 - In an emergency, you can even stop
 - High power and low area means you're less susceptible to up- and down-drafts for comfort
 - It also means there are more times you can fly
- It is considerably cheaper to build, or adapt space for, landing pads than runways
 - You're not hitting it at 100 mph, so it doesn't have to be paved
 - Most existing parking lots would work
 - Rooftop landing pads are quite possible
- And last but not least, it looks like a flying car ought to!

Electric fans with the power-to-weight ratios and reliability we need are new since the Sixties; this approach could not have worked then. There are some reasons to prefer an it to a direct-coupled turbine (either shaft or air) for the fans, even though latter is probably a bit more efficient. First is the much faster control reactivity of the electric fans, which translates into much better control in hover. Second is that you can afford enough batteries to power you down to a hard landing instead of a horrible crash in the case

of a turbine failure on takeoff. Third is that when we get around to building the infrastructure, we can transmit power via microwave to flying aircars and cut down the amount of fuel they have to carry. Airports might be the first places equipped with transmitted power.

Another major development since the Sixties is a whole-airplane parachute deployed by a rocket system. Such a thing is nice if you run out of gas in midair, or have engine trouble particularly at night or over forests or mountains. Engine failures could be extremely rare with new turbines. The main vulnerable points in a VTOL flight are taking off and landing (as they are for airplanes), where a parachute is of limited use. A usable alternative might be RATO-like one-shot rockets with enough oomph to cushion a landing, with the afore-mentioned batteries to provide control. [\[215\]](#) Of course, they wouldn't technically be RATO. Perhaps we could call them ... retro-rockets.

Autopilot

To Thuvan Dihn he explained that he had been but testing an invention of his own with which his flier was equipped—a clever improvement of the ordinary Martian air compass, which, when set for a certain destination, will remain constantly fixed thereon, making it only necessary to keep a vessel’s prow always in the direction of the compass needle to reach any given point upon Barsoom by the shortest route.

Carthoris’ improvement upon this consisted of an auxiliary device which steered the craft mechanically in the direction of the compass, and upon arrival directly over the point for which the compass was set, brought the craft to a standstill and lowered it, also automatically, to the ground.

"You readily discern the advantages of this invention," he was saying to Thuvan Dihn ...

—Edgar Rice Burroughs, *Thuvia: Maid of Mars*

Even my 40-year-old airplane has an autopilot that’s essentially the same as the Barsoomian one, with the exception of gently lowering the craft to the ground at the destination. The mechanical arrangements that allow a plane to fly a fixed heading and altitude have been around since the 1930s. The part that involves flying to a destination is a retrofit to a GPS. Modern commercial autopilots (not mine) are capable of landing the plane, or more precisely, “autoland” systems using up to three separate autopilots do so. The single drawback to autopilots is that they sometimes fail, and you have to be ready to take over in a hurry. The very first thing you need to learn about it as a pilot is how to turn it off. Mine has an emergency kill switch literally under my thumb on the control yoke, a power switch on the control panel, and a circuit breaker, in addition to the controls on the unit itself. As with the case of self-driving cars, the question isn’t when and whether the autopilot can be made perfectly reliable. It can’t. The question is when and whether it can be made more reliable than a human pilot. Can we have

autopilots in our flying cars that make them at least as safe as the cars we drive on the ground today?

Over the past decade the answer to this question has changed from “very likely” to “obviously.”

The average person isn’t a good pilot. Piloting is harder than driving a ground car, because we don’t have the instincts for flight the way we do for navigating on the ground.

Furthermore, the closer you get to a VTOL flight regime, the harder it is. Your author, in addition to getting a pilot’s license in researching this book, took the obvious step of acquiring a remote control quad-rotor (i.e. VTOL) drone and trying to fly it. It is significantly harder to fly without crashing than a conventional airplane, although limited space, displaced point of view, lack of kinesthetic feedback, and unfamiliar el cheapo controls surely aggravated the difficulty, not to mention that the controls on your remote are typically like those on a helicopter, i.e. reversed from those of an airplane. The history of experimental aviation, unfortunately, is littered with the wrecks of VTOLs crashed by experienced test pilots. But an automatic pilot could be built with a complete understanding of the dynamics of the flight regime and the capabilities of the craft, and direct connection to an artificial sensorium that tells it all about the patterns of airflow around the machine, as well as things like attitude and airspeed that a human pilot sees on his instruments. This could be far safer than any human pilot, much less a novice amateur one. Perhaps surprisingly, that is the piece of technology we already have. Commercial airplanes have had steadily improving autopilots for decades, to the point where on the average flight the human pilot isn’t actually necessary. With the recent advent of high-powered microcontrollers, lithium batteries, and high power-to-weight ratio electric motors, small fan-lift VTOL drones have proliferated. Along with all the commercial versions, there are plenty of hobbyists who are into “rolling their own.” So the control software for autonomous flying vehicles is available for free in open-source projects, and is being extended in its capabilities on an almost daily basis. [\[216\]](#)

Highways in the Sky

*From an I/T perspective, ATC is a functioning computing museum. Still lots of V.35, RS232/449/422, X.25, ATM, FDDI deployed. Stockrooms full of very olde, tired iron ... still in factory-new packaging. Ditto for programming languages. FAA apparently is willing to pay a pretty premium for *skilled* JOVIAL (language) programmers.*

—Doug Ranz

There are about 20,000 airports in the US, of which roughly 5000 are open to the general public. Only 500 or so offer commercial flights. In fact there are only about 6000 commercial airplanes. For comparison, there are about 3000 counties in the US, so there are on average between one and two public airports per county, and six or seven including private airstrips. There are on the order of four million miles of roadway in the US, of which about 2.6 million are paved. [\[217\]](#) The Interstate system comprises about 50,000 miles of this, and that and 100,000 miles of major state highways carries about half the traffic (vehicle-miles).

The contiguous 48 states have an area of about 3 million square miles. There are about ten miles of altitude accessible to aircraft (two to non-pressurized ones with normally aspirated engines—you and your engine get breathless at about the same point). Under current regulations airplanes need 1000 feet of vertical separation and 5 miles of horizontal (back of the envelope rule of thumb—actually the regulations are quite complex). These regulations are based on a technology where the pilot is looking at an altimeter and controlling his altitude manually (indeed flight levels are defined by barometric pressure, not actual height), and maintaining horizontal separation by verbal interaction with air traffic controllers. Physically, planes can safely fly much closer together if they are going the same speed and direction; think of geese flying in a V-formation. But let's take the current regs as a point of departure.

If you merely parceled out the airspace in lanes at these separations you would have on the order of 30 million miles of high-speed highway—200

times what we have on the ground.

That would mean there is room for six million aircraft in the air at one time (one million non-pressurized). If you cut the separations to a mile, which wouldn't be hard for good electronic controls, you'd have 150 million miles of lanes and the same number of aircraft in the air at once. That's more than there are cars on the roads.

Moulton "Aerocar" Taylor was of course right; the existing air traffic control system would completely break down long, long before that many private planes got into the air. It is surprisingly antediluvian for the twenty-first century. In an era when the distributed control of the internet routes and switches literally trillions of packets of information *per second* all over the planet, each interaction with ATC is done by voice in English with a live human being. This makes for a system that is often running at the outer edge of its capabilities. Recently [\[218\]](#) a disgruntled employee cut some cables in the Chicago Center and set fire to the building. This created a 91,000 square mile hole in the ATC system. More than 1000 flights were grounded while controllers scrambled to reach alternate facilities as far away as Kansas City. Besides being somewhat fragile and running near capacity, our current ATC system is not easy to expand. It would be simply incapable of handling the orders of magnitude more traffic that generally owned flying cars would involve.

Watch a flock of birds land on and take off from a field, or a seagull tornado doing a continuous rolling dive on a patch of delicious flotsam. It is clear that no possible human ATC could handle such collective flight patterns, but also clear that they are possible with purely local distributed control, using senses and reflexes not impossibly more capable than our own.

When you fly on a clear night you see quite a few more other airplanes than you do in the daytime. That's because they have big bright anti-collision strobes which are visible 25 miles away. With car-density traffic, such strobes would make the sky a confusing Las Vegas-like lightstorm, but they could be replaced with radar-frequency beacons that encoded your car's position, altitude, and course. Your autopilot could read these all in real time and know its situation vis-à-vis every other aircraft nearby at least as well as the seagull does, but on a scale 1000 times as large. We need, roughly, a factor of 20 for our car's speed (500 as opposed to 25 mph), leaving us with a factor of 50 to account for being slower to turn than the

seagull. Since we are not intending to be dogfighting, but just merging into and out of traffic flows, this should be plenty.

There are roughly 3 million square miles in the contiguous USA, and 200,000 cellphone towers. That makes one per 15 square miles, for an average distance apart of 4 miles. At cruising altitude you are in view of ten to a hundred of them most of the time. Put a box on each one that looks for and talks to all the aircraft in its area, very similarly as the cell tower already does for pocket phones. Add that to GPS and your flying car can always know exactly where it is, and where every other aircraft in the same state is, to within a foot. Add that to inter-car communication and all that remains is to work out the rules of the road.

ADS-B

It turns out that something like this scheme has been implemented for the North American airspace under the somewhat opaque acronym of ADS-B, for Automatic Dependent Surveillance — Broadcast. Instead of using the 200,000 cellphone towers, it uses 634 custom government-run ground stations. These provide coverage over much, but not all, of the continental US. By 2020, all aircraft operating in certain high-traffic areas (essentially the same ones that require a radar transponder today) will be required to be equipped with ADS-B-Out, consisting of a GPS receiver and a transmitter that broadcasts the plane's position and altitude into the system. Whenever that is done, about once a second, the system transmits position information about traffic in a "hockey puck" 15 miles wide and 3500 feet thick around the airplane back to it. Separate equipment to receive and display this information in your cockpit, ADS-B-In, is available but not required.

As it stands today, the ADS-B system provides air traffic controllers with more complete and accurate information about aircraft, and provides pilots with information they would not have had at all. To some extent, it is an existence proof that a decentralized system is possible, and is a step in the right direction. However, it basically replaces the existing radar network and feeds into the existing centralized air traffic control system. It would still require a major revolution at the ATC level to accommodate generally-used flying cars.

The best chance that has of happening today is by growing out of a decentralized system for drones. There are now ten times as many drones as manned aircraft. The FAA tells us about it:

How will a UAS traffic management system (UTM) work? UTM is how airspace will be managed to enable multiple UAS operations conducted beyond visual line-of-sight (BVLOS), where air traffic services are not provided. The FAA, NASA and industry are partnering to develop UTM to support the real-time or near-real-time organization, coordination, and management of primarily low altitude (< 400 ft AGL) UAS operations.

At the moment all it supports is automatic notification of airports of drone activities in the area, but given the pressure (and an increased willingness to experiment with drones), we may see some real advances.

——Bottom Line——

The bottom line is that a real, live flying car, VTOL and all, seems reasonably likely to have been possible with the technology we have today, much less the technology we could have had today had we continued to advance at pre-1970s rates. The big gap of course is power. Nothing else as brightly illuminates the gulf between the ergophobic religion that regards energy as some shameful original sin and the can-do attitude of the Fifties of “whatever it takes to get the job done.” It underscores the notion that energy poverty is one of the major things separating us from the future we were promised.

VTOL does make a difference. The convertible flying car is a replacement for the airplane; a helicopter or VTOL could be a replacement for the car. Paramount in the list above is the implication that you don’t need a big clearing of level land for an airport. Look at a topographic / demographic map of the US and you will notice that a large amount of the sparsely populated area is rough country, mountainsides, and the like. The entirety of New Zealand is like that, which is one of the reasons they lead the world in helicopters per capita. Obviously a vehicle that needs a runway is out of the question. But if you can put a landing platform on your roof, you can put a house anywhere.

And finally, if you put enough power into your flying car to go as fast as you would like to, it need not have any wings at all. Once again, *The Jetsons* got it right.

18 Metropolis

As in the pseudoscience of bloodletting, just so in the pseudoscience of city rebuilding and planning, years of learning and a plethora of subtle and complicated dogma have arisen on a foundation of nonsense.

—Jane Jacobs

At the turn of the twenty-first century, humanity passed a major watershed. For the first time, more than half of us lived in cities. While it may be that our far descendants will stand naked on the asteroids and float in the atmosphere of Jupiter, it seems a not unreasonable prediction to say that for the coming century at least, the majority of humans will live in environments that are for all practical purposes entirely artificial.

Towers

For they needed not the forests in which the Americans lived, nor the resources of the vast territories these forests covered. With the perfection to which they had reduced the synthetic production of necessities and luxuries, their remarkable development of scientific processes and mechanical accomplishment of work, they had no economic need for the forests, and no economic desire for the enslaved labor of an unruly race.

They had all they needed for their magnificently luxurious and degraded scheme of civilization, within the walls of the fifteen cities of sparkling glass they had flung skyward on the sites of ancient American centers, into the bowels of the earth underneath them, and with relatively small surrounding areas of agriculture.

Complete domination of the air rendered communication between these centers a matter of ease and safety.

—Philip Francis Nowlan, *Armageddon: 2419 A.D.*

Atom City! Built of the clear crystal mined so cheaply on Titan, moon of Saturn, Atom City had risen from a barren North American wasteland to become a show place of the universe. Here was the center of all space communications—a proud city of giant crystal buildings. Here had been developed the first slidewalks, air cars, three-dimensional stereos and hundreds of other ideas for better living. And here at Atom City was the seat of the great Solar Alliance, housed in a structure which covered a quarter of a mile at its base and which towered three thousand noble feet into the sky.

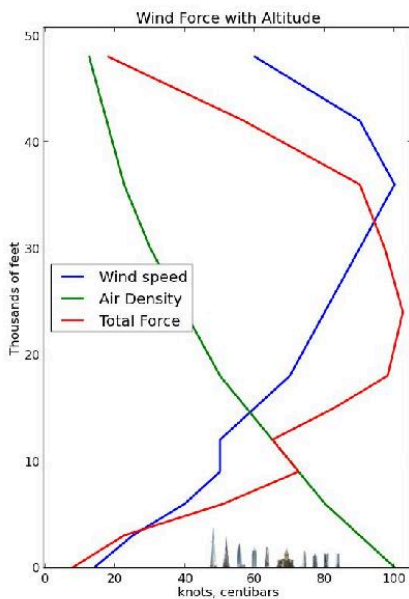
—Carey Rockwell, *Stand by for Mars!*

The Burj Khalifa in Dubai opened in 2010 as the world's tallest building, about half a mile high. It broke the record for highest building in 2007, while still under construction, taking the pride of place from Toronto's CN Tower, which had held it since 1975.

Except for being only half as tall, it resembles Frank Lloyd Wright's mile-high tower in overall shape—but of course the Burj is real. From what I can tell, it could not only house but form the complete social and economic infrastructure for about 5000 people, if it were designed with that in mind. In reasonable luxury—the actual Burj contains 900 luxury residences as well as 37 floors of offices. In a shape that wasn't quite so needle-like (e.g. almost any other building) you could have an average of an acre of space per floor, house 25 people per floor with 1000 square feet per person with plenty left over for public and utility space. That gives the Jetsons their 5000 square foot apartment if you count Astro as a person. There are 200 stories in the naked city...

Scale it up to a mile and you're talking 40,000 people.

Given its elegant shape, the Burj has an incredibly tiny footprint (the foundation slab, not the surrounding plaza) of less than two acres. It seems reasonable to imagine that one could build a mile-high version with a 7-acre footprint. Put only one of these per square mile—it takes up about 1% of that area, so the land is left pretty much untouched—and you could house the current population of the Earth in about the area of Montana. Give people flying cars and/or underground high-speed trains to get from one tower to another, and you really could turn the whole Earth into a park not unlike Buck Rogers' America—a *Jetsons'* world indeed.



Transverse wind and relative force (proportional to density and the square of the speed) on a particular day at my location. The tower on the left is the Jeddah Tower, currently under construction; the Burj is second.

A major engineering load on a tall building is wind, and it gets bigger the taller the building. Even though the top is slender openwork, at the second platform level the structural members on the windward side of the Eiffel Tower are in tension, not compression. [\[219\]](#)

This is the primary reason that modern skyscrapers are built in interesting shapes, with twists, holes, anything except a simple rectangular parallelopiped. Yes, it does make the building look more interesting, but the main effect is to break up the buffeting vortex street generated by the simple regular shape, and significantly reduce dynamic wind loads.

Wind loading rises alarmingly until about 20 thousand feet (4 miles), plateaus until 40 thousand, and decreases thereafter as the air is much less dense than at sea level. Somewhere between 5 and 10 thousand you begin to have to pressurize the building for people to live in it. (Alternatively, you could increase the oxygen fraction of the interior air to maintain the sea-level partial pressure of 6.28 inches of mercury, 210 millibars. This would work up to about 35,000 feet, i.e. seven miles.) So you have to be able to do a lot of high tech building, and the people have to be pretty wealthy.

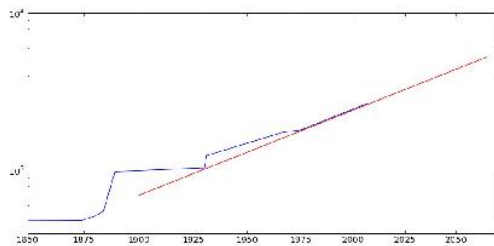
Building a world full of mile-high towers with current technology would strain the world's supply of steel and concrete significantly, if it were possible at all. With nanotech, though, it would be pretty straightforward. Some years back I suggested that a good X-prize for nanotech would be to build a tower ten miles high. The reason was that you'd have to come up with a working manufacturing method to make the material, probably nanotubes and diamond, cheaply.

It turns out that that might have helped but may not be necessary. Materials science of the type sometimes called "nanotechnology" has advanced rapidly over the past decades (and yes, an understanding of materials at the nanoscale is a good part of it). One thing apparently in the works is an aluminum-steel alloy that might be produced at steel prices but with strength-to-weight properties resembling titanium. [\[220\]](#) With this you could build a version of the Eiffel Tower (the 984-foot original is of

wrought iron, with max design stress of about 10 ksi, which gives it a safety factor of three) over a mile high with no design modifications besides simple scaling. Optimizing it would very likely make ten miles possible. It's not so much the strength-to-weight ratio of the new materials you need, however, but something else. I received enlightenment when I talked to a skyscraper structural engineer, who told me, "Steel is light." That was a jarring revelation to someone, me, who had been studying airplane design, but the point of comparison is concrete (for the same strength). But steel is also springy; a ten-mile steel structure would handle gravity just fine, but would whip around in the wind like an old-fashioned radio antenna. You might get a great view from the 520th floor, but you have to watch out for seasickness. The concrete gives you both stiffness and inertia.

The Burj Khalifa used a recent advance, the ability to make concrete of higher strengths than before (and pump it further). Use of diamond or nanotube composites in that role would enable much higher towers. When can we expect mile-high, or ten-mile-high, towers?

The surge in building heights coincided with the industrial revolution and the use of iron and steel in building, as exemplified by the Eiffel Tower. Here are tallest buildings on a semi-log scale:



The blue line is tallest building (height in feet), the red is an eyeball-fitted trendline. This puts the tallest building at a mile in about 2065—just right for the Jetsons. However, all the structures in this trend are steel-and-concrete, and so, even though they follow an exponential curve, a shift into nanomanufacturing and materials could easily kick the curve into a different mode. We could even see a major jump, like the Eiffel in 1889, if someone took the new capabilities and set out specifically to build a structure just to be impressive. Or as a space launch tower.

A ten-mile tower might have a footprint of a square mile and could house 40 million people. Eight such buildings would house the entire current population of the United States, leaving 2,954,833 square miles of land available for organic lavender farms.

This would definitely be an undertaking worthy of twenty-first century technology; but the technology we need the most is a governing, managing, planning, and maintenance ability that is honest, competent, and trustworthy. Otherwise when Detroit falls over onto Windsor, Ontario, it causes an international incident with who knows what kind of domino effects.

I look forward to designing a mile-high building.

—Dennis Poon, lead engineer, Chengdu Tower

City

Cars didn't shape our existence; cars let us escape with our lives. We're way the heck out here in Valley Bottom Heights and Trout Antler Estates because we were at war with the cities. We fought rotten public schools, idiot municipal bureaucracies, corrupt political machines, rampant criminality and the pointy-headed busybodies. Cars gave us our dragoons and hussars, lent us speed and mobility, let us scout the terrain and probe the enemy's lines. And thanks to our cars, when we lost the cities we weren't forced to surrender; we were able to retreat.

—P. J. O'Rourke

Many of the classic SF writers expected automatic package delivery. Philip Francis Nowlan, in the original *Buck Rogers* novels in 1927, wrote [\[221\]](#)

Why should he leave his house? Food, wonderful synthetic concoctions of any desired flavor and consistency (and for additional fee conforming to the individual's dietary prescription) came to him through a shaft, from which his tray slid automatically on to a convenient shelf or table.

At will he could tune in a theatrical performance of talking pictures. He could visit and talk with his friends. He breathed the freshest of filtered air right in his own apartment, at any temperature he desired, fragrant with the scent of flowers, the aromatic smell of the pine forests or the salt tang of the sea, as he might prefer. He could "visit" his friends at will, and though his apartment actually might be buried many thousand feet from the outside wall of the city, it was none the less an "outside" one, by virtue of its viewplate walls. There was even a tube system, with trunk, branch and local lines and an automagnetic switching system, by which articles within certain size limits could be despatched from any apartment to any other one in the city.

Interestingly, Nowlan also predicted radio-controlled flying drones, but only as military equipment, not for package delivery. But it was a common theme in early-to-mid 20th Century SF to imagine a city as an engineered transportation infrastructure capable of moving everything from packages to people automatically from place to place.

The value of a city is not to bring people closer together. All other things being equal, I am better off with more space to operate and more distance between me and my snoring neighbor—or the busy pub at 2 AM, or the sirens telling strangers to get out of the way of an ambulance carrying other strangers. (Or, according to reports, disguising a fast luxury limousine service.)[\[222\]](#) Space in cities is at an incredibly expensive premium—land in Manhattan costs 25,000 times as much as in rural Montana. The ingenuity (and extra cost in time and effort) with which people fit homes and businesses into cramped and oddly-shaped places in cities is remarkable.

I've had a modicum of experience in New York City. A few years back I noticed an interesting thing: you could tell, without any reference to external views or other such prompts, whether the cocktail party you were attending was in the city. If the most common single topic of conversation was the weather, you were elsewhere. If it was traffic, you were in New York. Megan Mcardle, in a retrospective of life in New York, points out how dysfunctional intra-city transportation has become: [\[223\]](#)

That Saturday night I had three parties to go to, in three parts of the city. I was determined to pack them all in, because when would I see these people again? It took an hour and a half to get to the first one, in Cobble Hill. Inwood and Astoria clearly were not going to happen. As I made that calculation, the incipient panic I'd felt at leaving "all that" vanished, as my city already had. The bits of New York that weren't turning into a shopping mall were instead turning into London, where the cost of real estate pushes the merely affluent people so far to the periphery that it is only really practical to make friends along a single train line.

From Cobble Hill to Astoria is 6.5 miles, as the crow flies. From there to Inwood is another 7. Mcardle could easily own a car which could do the

total distance in 8 minutes, if only there were an open road. In the absence of one, a helicopter could do the same. One would think that with the density of prospective riders, economies of scale would allow a well-designed and integrated transportation system to do better than private independent vehicles going between ranch houses across the open plains. Instead it does an order of magnitude worse.

The value of a city is to reduce the time, the opportunity cost, to get from one place—a home, business, institution, restaurant, recreation—to another. It's pure travel theory. In fact, the only significant variation from the general travel theory rule that the average person travels 1.1 hours a day, anywhere, is in cities, where they travel a little bit more. That's consistent with the hypothesis that there are more valuable destinations for a given amount of travel time taken.

The current leading ideology of city planning, unfortunately, is completely oblivious to this. In fact the high-density “smart growth” school of thought could reasonably be summed up as motivated by making travel as difficult, rather than as easy, as possible. Like many of our legally-latched social pathologies today, this one has the structure of a Baptists and Bootleggers bedfellowship. The bootleggers are obviously the public transit industry like the “Portland light-rail Mafia,” the politicians supported by their lobbying, and developers benefiting from subsidies and the power of eminent domain. But who are the Baptists?

They are to a large extent the followers of Jane Jacobs, the guru, one might even say patron saint, of densification and walkable neighborhoods that foster thriving communities. In her last book, *Dark Age Ahead*, for example, she tells the horrific story of the 1995 Chicago heatwave, which killed something like 1000 people, mostly elderly, of heatstroke and dehydration. It turns out that the deaths were clustered in dysfunctional neighborhoods, such that the people were found in tightly locked apartments, without friends to help them and too afraid to go out even to seek refuge in an air-conditioned store.

One doesn't need to go the extremes of a killing heatwave to understand that a dangerous, dysfunctional neighborhood is a lousy place to live. An old-fashioned Elm Street where people sit on their front porches and exchange friendly greetings with pedestrian passersby, is an enormously more desirable home. This is of course what you get in small towns, and is

a major reason that people are happier there than in cities. Just as with radiation or regulation, a moderate amount of other people is beneficial, but an overload is not.

Jacobs is generally read as saying that cars kill communities; this is due to two distinct phenomena. First was that putting a highway through the middle of a neighborhood physically separated it, destroyed part of it, made it unwalkable. Second was that once you got into your car, you didn't interact with people, and the community bonds of familiarity and acquaintance didn't form.

This last is particularly why she didn't like suburbs. I can relate to the basic logic of the problem; I lived in suburban New Jersey for 20 years and never met my next-door neighbors. There was nowhere you could go without a car. But those years were far from lonely, non-communitarian ones; in fact they were probably the most connected part of my life. It is just that the communities I was part of were based on cars, from the restaurants I frequented in nearby towns, to the tennis club, to the university where I learned, worked, and taught. All of my friends had cars too; guests were frequent at my house. The difference was that these communities, like the ones that were just then beginning to spring up online, were voluntary; they were formed by people who sought out the same things and had common interests.

Jane Jacobs did not drive or own a car. It's not surprising she would have missed the nature of the extended community. If you walk everywhere, you are limited to a literally medieval radius of a mile or so for day-to-day travels. With a car, your radius is 20 times as large, and the area of your community 400 times. Your friends are just as accessible, for fun and for help, because they have cars too. The elderly are safer, and feel *much* safer, in their cars than walking in a bad neighborhood. If the poor folks in Chicago had had cars, they could have gotten into them, turned on the air conditioners, and headed for cooler climes.

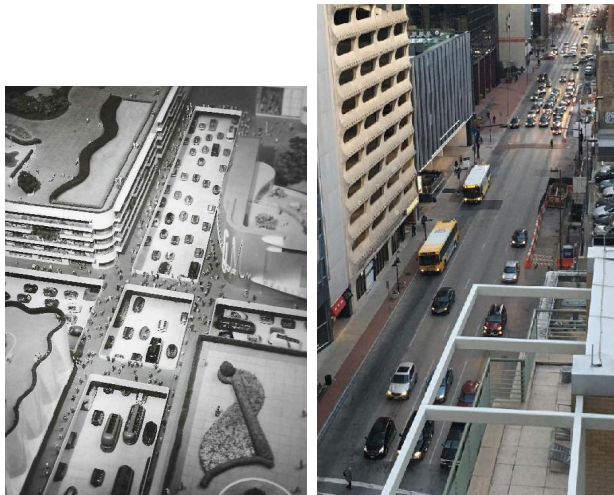
What about putting a superhighway through the middle of a neighborhood, destroying its pleasant boulevard? Dare I mention flying cars? The traffic on the superhighway neither originates nor terminates in the neighborhood. The cars that would have been on the highway will, in a properly designed system, be invisibly high above our delightful neighborhood.

Knowing all this, then, how would you design a city? Clearly the first, not last, item of concern is the transportation infrastructure, because the only reason for a city is to reduce the time to get from place to place.

A system designed for the benefit of its customers might look more like this: Lighter rails, built for car-sized vehicles instead of train-sized. They could be cheaper, more numerous, and run overhead instead of intersecting existing streets. All the vehicles are autonomous car-sized pods, taken individually on demand, which go from any station to any other without stopping in between. Having the stations off the main travel tracks has several advantages, notably faster travel times, because no stopping, and lower latency because there are always a few pods waiting at each station. The system as a whole could have a much higher carrying capacity than one with trains and stops, simply due to increased rail utilization. More to the point, it could have been nearly as valuable to its riders as having cars. Technologically, this could have been done in the 60s, and indeed was, in prototype, at places ranging from Disney to RCA. It was too expensive then, but given how much we've poured down the rat-hole of worthless light rail since then, we might as well have given it a try.

The greater Dallas-Fort Worth metropolitan area has an area nearly 3000 square miles. If you are on foot, about 5 of those are available to you. In a car, with present congestion that gives you an average speed of about 20 mph, travel theory tells us that you'll have about 380 square miles from which to choose daily activities. A well-designed road system, allowing cars to get their normal effective point-to-point speed of 40, gives you 1500, half the total. A helicopter, or any low-latency VTOL with a travel speed of at least 100 knots, would give you access to essentially all 3000.

I've never designed a city, but I've designed a number of processors and circuit boards. From a circuit designer's point of view, actual cities are primitive, indeed antediluvian: there's only one level of interconnect (with occasional jumpers). Even the Altair 8800 I built in my dorm room in the 70s had two levels on its processor board, and today's typically have something like ten.



Norman Bel Geddes' Futurama in 1939 depicted a city with multilevel interconnect and separate pedestrian levels. Today's real-world single-level cities remind one of the primitive printed circuits of the 60s: half the vehicles are standing still at any given time.

Even two levels in a city—one for north-south traffic, and one for east-west, say—would cut transit times in half. Heinlein's 1938 utopia predicted, or perhaps prescribed, this. Norman Bel Geddes designed Futurama the same way. E. E. "Doc" Smith concurs, by implication: "Northport was not a metropolis, of course; but on the other hand it did not have metropolitan multi-tiered, one-way, non-intersecting streets." (*First Lensman*) A separate level or levels for pedestrians, perhaps with *Looking Backwards*-type awnings when it rains, could make walking around town a quicker, safer, [224] more pleasant experience, not having to spend the extra time waiting for traffic, or go the extra distance of crossing roadways. Given people's revealed preferences, pedestrian levels should probably look more like shopping malls than the useless greenspace that looks so pretty in planning committee models (although greenery is valuable in other contexts; see below). On this point I turn out to be in complete agreement with Jane Jacobs; in fact I was quite surprised once I started reading her in depth just how much I did agree with her. [225] She turns out to be one of those major original thinkers whose insights are misunderstood, oversimplified, and misapplied by "followers" who quickly migrate from the Baptist to the Bootlegger side of the equation.

You have to compare the progress in manufacturing or electronics or software over the past half century with the state of the art in city design and operation to get a sense of just how stagnant the latter has been. Even the recent flurry of Utopia-building projects are still basically rows of boxes sitting on the dirt plus built-in wifi so the self-driving cars can talk to each other as they sit in automated traffic jams. Look at a brain, where most of the space is taken up by wiring. Look at a human body, where most of the space is taken up by tubes of one kind or another to move various stuff from one organ to another. Look at a processor chip, a circuit board, a chemical plant, the engine compartment in your car. Designing a city whose transportation infrastructure consists of the flat ground between the boxes is insane.

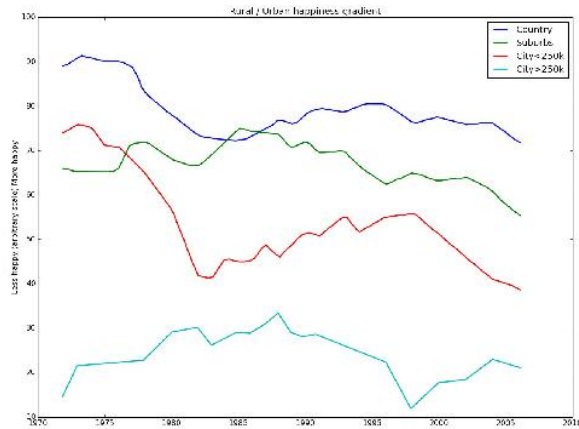
Intelligently managed, with a Henry Adams Curve technology and economy, cities should be machines for facilitating commerce and social interaction. But well-designed cities, with integrated transportation such as “moving ways” and multi-level streets, are clearly among the high-energy, high-technology futures we were promised [\[226\]](#) but failed to achieve.

Diaspora

I think it's cathartic to design a dark future, sort of a "glad it didn't happen to me" situation, [but] to design a nice future is a lot more difficult.

—Syd Mead

Unfortunately, our current-day cities are among our poorest-performing technologies. Psychological surveys show that people in the country or small towns are happiest, those in big cities are the least happy, with medium-sized cities in between:



Self-reported happiness in the General Social Survey

Not only are people happier in the country, it's healthier too. You are approximately three times as likely to be murdered if you are in the 50 most populous municipalities in the US as elsewhere. A recent study by Peter James *et al* of the Harvard University Chan School Department of Epidemiology found (somewhat to their surprise) that "People whose homes are surrounded by the most greenery are 13 per cent less likely to die of cancer. Their risk of dying from respiratory disease also drops by 34 per cent, the biggest ever study into green spaces and health has shown. Overall mortality was 12 per cent less for people who had the most greenery within 250 metres of their homes," all other things being equal. [\[227\]](#) Note the emphasis on homes.

In today's technology, cities and cars are enemies. Every increase in density makes congestion worse and slows cars down. A tower city would be the apotheosis of this trend, making cars useless. On the flip side, the car makes the city less necessary, as the mid-century rise of suburbia demonstrated. You could get the same travelability as a crowded, highly-connected city by building your city as a loose cluster of *Jetson*-like towers in which each home and business had a flying car garage that opened directly to the sky, but which internally fostered ~250-person pedestrian communities. This keeps you from having to build ten levels of highway; just use the airspace. What doesn't work with ground cars does work with VTOL flying cars. We now have the technology to do most shopping online and delivery with drones, if you have a home with a rooftop landing pad or the equivalent in

your backyard. In a readily foreseeable future, nanotech begins finessing even this with ever-more-capable 3D printers. Similarly, the restaurants, theaters, and workplaces you might want to attend—and your friends!—would be just as easily accessible with your VTOL flying car as they would be walking in a city, but perched on a mountainside among the trees 25 miles away.

Islands

Current technology is perfectly capable of building seagoing cities; that's what a cruise ship is. Boats or platforms built with current maritime technology are feasible but expensive compared to most (but not all) land-based housing. The places that are more expensive are so because of economic network effects and land-use regulation, *e.g.* London, Tokyo, New York, San Francisco, Silicon Valley. What economic advantages of a sea city might mitigate this?

At the Seasteading Institute, the original motivating advantage was lack of (incompetent) government. We can estimate that this might be worth about a doubling of the economic growth rate compared to the US. But that's only going to help if the total cost of doing business can be brought down to within say 3% of what it is elsewhere. Other factors of production must be found that have advantages hard to find on land.

The obvious big advantage is lots of free space. Your seastead estate can be as big as you like, if you can afford a private structure. (And there's no grass to mow.) Here's where technology comes in. As we get closer to true nanotech, the cost of a deep-ocean houseboat should fall, where most of the cost of homes on land is location.

Mobility is a second big advantage, and this also argues for individual (or smaller-group) structures. Mobility gives you good climate all year round (just follow it) and the dynamic geography that the seasteaders hope will ameliorate government lock-in.

Someone living on a cruise-ship-sized floating city can walk to everything but there's not so much there—a city of a few thousand people is quite small as cities go. A distributed community of seasteads, including larger platforms acting as apartment houses, malls, factories, and so forth, would need a transportation technology equivalent to cars and trucks. For heavy freight there are ships, of course, but for fast light freight and personal transportation you'd almost certainly prefer seaplanes. No need to build expensive runways or technologically challenging VTOLs. Seaplanes are a reliable technology we've had for over 80 years—and we can almost certainly improve on them.



Your flying car, if you live on a seastead. In fact, a PBX-size seaplane would make a nice houseboat.

(A U.S. Navy Consolidated PBX-5A Catalina: U.S. Navy Naval History and Heritage Command)

Automatic piloting and cheap power would put the seaplane in the category where improving technology made it feasible as the “family car.” And that in turn makes seastead communities possible in a much more distributed form, with lower barriers to entry (and exit).

And that’s without even thinking about nanotech. With molecular sorting, isotopic separation, and nuclear processes, seawater contains as much energy per gallon as gasoline, mostly as deuterium, lithium, boron, and uranium. It also has a wealth of other dissolved minerals in trace amounts that a nanofactory would need to augment the abundantly available carbon, hydrogen, oxygen, and nitrogen that would comprise the bulk of its products.

Of course, technology doesn’t develop itself—people need to be trying to solve problems, and the problems of seasteading are only beginning to be looked at. Given sufficient interest, however, it seems likely that the technology for dynamic, economically viable ocean communities might be available fairly early in this century, and for completely self-sufficient family-sized units in the later decades. As a futurist, one of the biggest underpredictions I see for the coming century is the extent to which we

begin to colonize the seas. The one Golden Age writer who thought much in this direction was Clarke; but as usual, Jules Verne led the way.

The sea does not belong to despots. Upon its surface men can still exercise unjust laws, fight, tear one another to pieces, and be carried away with terrestrial horrors. But at thirty feet below its level, their reign ceases, their influence is quenched, and their power disappears. Ah! sir, live—live in the bosom of the waters! There only is independence! There I recognise no masters! There I am free!

—Jules Verne’s “Captain Nemo”

The Pacific Archipelago

The ocean liner could be updated to a self-sufficient seagoing city in the 21st century, but it remains basically a Victorian technology. With nanotech, we could do a bit better. An island, after all, is just an arrangement of atoms. Dig mile-deep and -wide trenches on the seafloors and use the material to build islands. If you did enough of it, you might even lower the sea level a tiny bit. Mountainous shorelines from California to Hawaii to New Zealand are considered among the most desirable places to live; we could easily fill the Pacific with mountainous islands, barely visible from each other. All easily accessible in our flying cars, of course.

Where are we going to get the energy to do this? The sea floor appears to contain concentrations of uranium ranging from 5 to 500 PPM, [\[228\]](#) making it contain *much* more usable energy than if it were solid coal. And you are digging it up anyway.

Islands in the Sky

Consider an aircraft with a ten-mile wingspan. It might be a “flying wing,” perhaps shaped like a manta ray. It might have a chord of five miles at the center and a thickness of up to a mile. Internally, there is enough volume for say 4400 square miles of floor area (in 10-foot stories). That is room enough for about 10 million people at 12,000 square feet apiece, room not only for staterooms but 250 levels of “one-way, non-intersecting”

roadways, service cores, 50,000 elevators, and cathedral-like atrium spaces. A 747 weighs about 1000 pounds per passenger; let's budget 5 tons per citizen. That gives us a wing loading of about 150 pounds per square foot, same as the 747.

Given the ridiculous wingspan and the virtually infinite Reynolds number, we might get a lift-to-drag ratio of 100; we would need 1 billion pounds of thrust. With two square miles of thruster area, i.e. a 1000-foot-wide strip running the entire wingspan, that's 36 pounds per square foot. Checking our disc-loading graph, we will need about 250 million horsepower. Call it 200 GW with enough left over to keep the lights on. That's just 25 hp (19 kW) per person, or just about where we should have been now on the Henry Adams curve. It might be barely possible with chemical fuels, but one single line of nuclear power plants (every 250 feet) along the wing would suffice to keep Aero City flying indefinitely. That sounds like a lot, but they would occupy only 0.01% of the internal volume of the city.

It would strain the world's resources to build Aero City in current technology, but it would more or less straightforward with a mature nanotech. Would you want to live there? I know not, but it stands as an existence proof that we could live in luxury and leave the entire surface of the Earth untouched.

——Bottom Line——

As a user of transportation, I want it to

- start right at my door,
- at exactly the time I need it,
- stop right at my destination,
- be as fast as possible,
- force me to interact with as few other people or vehicles as possible; in other words, be able to use the time to eat, sleep, read, or work as much as possible.

This last is the crux of the tension between the densification proponents and the notion of a better world as seen by someone who has to live in it. There is a perverse incentive for bureaucrats and politicians to force people to interact as much as possible, and indeed to interact in contention, as that increases the opportunities for control and the granting of favors and privileges. This is probably one of the major reasons that our cities have remained flat, one-level no-man's-lands where pedestrians (and beggars and muggers) and traffic at all scales are forced to compete for the same scarce space in the public sphere, while in the private sphere marvels of engineering have leapt a thousand feet into the sky, providing calm, safe, comfortable environments with free vertical transportation.

There is of course the opposing fact that forcing people to interact in a neighborhood tends to make it a better neighborhood. But that is much more appropriate for a village of 250 than a metropolis of 10 million. (If I'm reading her right, this is another point of agreement I have with Jacobs.) An apartment building can in my experience be a functioning community, if designed and run properly (or of course a hellhole if not). The question of whether you get from your building to similar communities and other businesses by moving ways or flying cars is orthogonal.

Densification proponents often point to an apparent paradox: removing a highway which crosses a community often does not increase traffic on the remaining streets, as the kind of hydraulic flow models used by traffic

planners had assumed that it would. On the average, when a road is closed, 20% of the traffic it had handled simply vanishes. Traffic is assumed to be a bad thing, so closing (or restricting) roads is seen as beneficial.

Well duh. If you closed all the roads, traffic would go to zero. If you cut off everybody's right foot and forced them to use crutches, you'd get a lot less pedestrian traffic, too. If you make something more expensive, in time and effort no less than in money, people will demand less of it. It's pure travel theory, of the kind I developed in Chapter 11 in connection with flying cars. The only surprising thing about it is how the planners' traffic flow theories can have missed this crucially basic economic fact.

Build more roads and you will get more traffic. The new traffic represents people now able to do things they wanted to do but could not, before, afford the cost in time. Keep building roads until the total traffic does not increase when you add a new one. Then you'll have the optimum traffic capacity for the capabilities of the cars. Of course, roads are not free, either in money or measured as an opportunity cost in contention with other land use. So you need to balance road cost with value. But no one in their right mind who has any experience with electronic systems design (or who is familiar with nerve pathways in the brain, the majority of which is interconnections), could imagine that one flat, highly contentious level is optimal for a large, dense, high-traffic system. One might say ten levels as a wild guess in analogy to processor boards, but even two would be a quantum improvement.

The bottom line is that a properly designed city might have ten levels of traffic interconnect (with parking between travel lanes), a level or two of pedestrian shopping and boulevard sidewalk cafes, and spires towering above that. Travel time from point to point might be a third that in current cities, with the result that the value of living there might be 10 times as great. This, of course, requires a lot of machinery. But then what did you think we were going to do with a technology capable of replacing the current capital stock of the US in a week, anyway?

The average American commute to work, one way by car, ranges from 20 minutes to half an hour (the longer times in denser areas). [\[229\]](#) This gives you a working radius of about 15 miles, or 700 square miles around home to find a workplace (or around work to find a home). With a fast VTOL

flying car, you get a 150-mile radius or 70 *thousand* square miles of commutable area.

Cars, trucks, and highways were clearly one of the major causes of the postwar boom. It isn't perhaps realized just how much the war on cars contributed to the great stagnation—or how much flying cars could have helped prolong the boom.

There should be no more reason for a motorist who is passing through a city to slow down than there is for an airplane which is passing over it.

—Norman Bel Geddes

19 **Escape Velocity**

*Witness this new-made world, another Heav'n
From Heaven Gate not farr, founded in view
On the clear Hyaline, the Glassie Sea;
Of amplitude almost immense, with Starr's
Numerous, and every Starr perhaps a world
Of destined habitation.*

—Milton, *Paradise Lost*, (1674)

*Let us create vessels and sails adjusted to the heavenly ether, and there
will be plenty of people unafraid of the empty wastes. In the meantime,
we shall prepare, for the brave sky-travellers, maps of the celestial
bodies.*

—Kepler, letter to Galileo (1610)

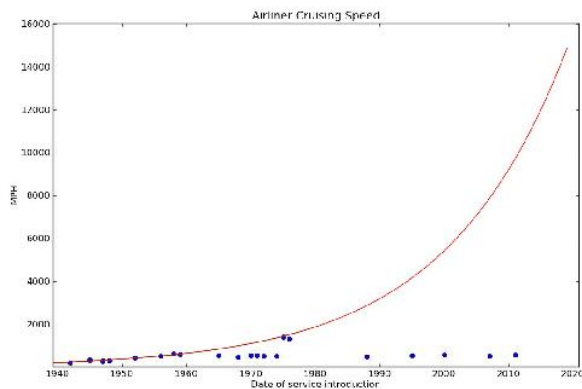
*In spite of the opinions of certain narrow-minded people, who would
shut up the human race upon this globe, as within some magic circle it
must never outstep, we shall one day travel to the moon, the planets,
and the stars, with the same facility, rapidity, and certainty as we now
make the voyage from Liverpool to New York!*

—Jules Verne

How can we futurists be so carelessly optimistic about the wonders of technology to come when there has been, in space travel, the most visible and highly hyped of technological applications as of 1962, not progress but a very evident evident regress?

With space travel, there's a pretty straightforward answer: the Apollo project was a political stunt, albeit a grand and uplifting one; there was no compelling reason to continue going to the moon given the cost of doing so. The nature of political stunts is such that it does you no good to repeat one, even if you can do the same thing better or cheaper or whatever.

There was something in the nature of a Lewis and Clark expedition in the moon landings, in that they surveyed the territory, not just physical but the technological territory of space flight. Notions of what a moon landing would look like changed drastically from the SF of the 50's to the actuality of the 60's. But in a sense, Apollo was too grand—the technology was way, way beyond what would be commercially viable for decades to come:



Airliner speed curve, with flatline, as seen in Chapter 3, but with the curve extended to date. Low Earth orbital velocity is about 17,500 MPH.

As you can see from the airliner cruising speed trend curve, we shouldn't have expected to have commercial passenger space travel yet, even if the Great Stagnation hadn't happened. The interesting part of the curve, though, is that the curve itself represents the capabilities of the underlying technology—which didn't stop. We should expect real services to reappear along the same curve if and when the capabilities meet a regime that has favorable economic properties.

They are about to: the curve should get into low-earth-orbital speeds in the coming decade, and orbit is an extremely efficient way to travel. It takes no more energy, total, to get to orbit than a 747 does dragging its bulk through the atmosphere halfway around the world—and you get to, say, Sydney, in under an hour instead of over 20. The beginnings of the commercially viable space travel can be seen in the companies trying to do X-prize-like suborbital joyrides—but the major impetus will come when the capability hits orbit and can land you somewhere other than where you took off. This

will happen, at best guess, sometime in the 2020s. (Unfortunately, orbital speed is an even deeper rut than subsonic; if you go faster, you need to use energy to hold you *down* to an orbit. At about 25,000 mph—around the world in an hour—you get a negative one gravity, which would at least be comfortable if you had the power to spend (e.g. an upside-down airplane). Much more than that and you're subjecting your passengers to high Gees.)

Rocket Science



The fuel pump in the V-2 rocket was rated at 800 horsepower.

You are standing in the middle of the air, ten miles up. Unfortunately, you will immediately start to fall. You would like to prevent that.

Fortunately, you are standing on a large rock, which weighs as much as you do. Before you and the rock fall much, you jump, pushing off of the rock. It falls faster than it would have, and you stay up.

Unfortunately, you can only jump so hard. You only stay up for a second before you begin to fall again.

Fortunately, you are holding another rock.

Unfortunately, that means we were wrong about the first rock. It didn't weigh as much as you do; it weighed as much as you and the second rock, i.e. twice your weight. So you and both rocks weigh four times what you do alone.

Fortunately, your legs are strong enough to jump off the big rock with your load at the same speed, and you stay up just as long.

Unfortunately, to stay up another second, you need have started with an even bigger rock; it has to be the total weight of you and all your other rocks. For each extra second you want to stay up, you have to double the weight of the rocks. For five seconds, 32 times your weight. For ten seconds, 1024 times.

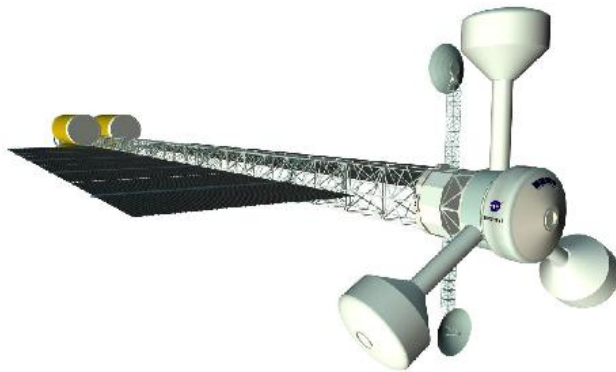
And that's why they call them rockets. In the standard jargon, your *specific impulse* is the velocity at which you can jump off the rock, measured in seconds before you need to jump again; in our example it was 1. The mass

ratio is just the total amount of rocks you bring, in multiples of your own weight.

In real life, the specific impulse of chemical rockets ranges from 300 to 400 seconds.

Nuclear rockets

Virtually every technically literate SF writer in the Fifties assumed that we would be using nuclear-powered rockets to explore the Solar System. Heinlein's first published novel, and his only movie, featured them in some detail. But probably the best of the lot was a somewhat more obscure writer named Hal Goodwin (under the pseudonym Blake Savage). Like Isaac Asimov, Goodwin was a practicing scientist as well as a writer; but while Asimov was a biochemist, Goodwin was actually director for atomic test operations for the federal Civil Defense Administration, later moving to NASA. His 1952 boy's adventure novel *Rip Foster Rides the Gray Planet* was the best account of nuclear spaceships that I read as a boy. It was the first place I ever heard of thorium, of using nuclear charges to alter the orbits of asteroids, of decontamination, or of radiation sickness.



“Discovery II” 2001 NASA fission-powered spacecraft design; the panels are radiators, not solar collectors. (NASA Glenn Research Center)

Probably the best-known design of a nuclear-powered spaceship capable of travelling throughout the Solar system is the *Discovery One* in Clarke and

Kubrick's film *2001: A Space Odyssey*. The design of the ship, with the propulsion unit, including nuclear reactor, at the back, and the crew quarters at the front, separated by a long thin section bedecked with reaction mass tanks, is predicated specifically on separating the crew from the reactor's radiation without an enormous mass of shielding. Frederick Ordway, a NASA engineer (and member of Wernher von Braun's staff) who did much of the design work for the fictional craft, wrote:

The Cavradyne engines are based on the assumption of years of research and development, during the 1980's and 90's, of gaseous core nuclear reactors and high-temperature ionized gases. Theory is presumed to have showed that gaseous uranium 235 could be made critical in a cavity reactor only several feet in diameter if the uranium atomic density were kept high, and if temperatures were maintained at a minimum of 20,000 degrees F. At first, progress was slow because of such early unsolved problems as how to reduce vortex turbulence in order to achieve high separation ratios, and how to achieve adequate wall cooling in the face of the thermal radiation from the high-temperature ionized plasma. In the Cavradyne system, the temperature of the reactor is not directly limited by the capabilities of solid materials, since the central cavity is surrounded by a thick graphite wall that moderates the neutrons, reflecting most of them back into the cavity. Wall cooling is ensured by circulating the hydrogen propellant prior to its being heated. Fissionable fuel energy is transferred to the propellant by radiation through a specially designed rigid—and coolable—container. [\[230\]](#)

The NERVA design experimented on in the 60s was in fact “limited by the capabilities of solid materials” and only managed to get a specific impulse of about twice (800 as opposed to 400 seconds) that of chemical rockets. [\[231\]](#)

Needless to say, the 80s and 90s did not see “years of research and development of gaseous core nuclear reactors,” as Ordway expected. Even so, nuclear thermal rockets are the only demonstrated technology capable of navigating the solar system in anything like reasonable times. In 2001, NASA published a technical report on a new spacecraft design. [\[232\]](#) It

reiterates some of the idiosyncratic elements of the original, which it shares with most of the conceptual nuclear spacecraft designs of the Sixties.

No one has demonstrated a nuclear-to-electric-to-ion rocket yet, but it would be the obvious next step. Current prototypes indicate that you could get an Isp of 3000 seconds or so.

The ultimate reaction rocket, however, is most likely to be a direct fission-to-jet process, using for example the proton + lithium-7 fission reaction producing 2 alphas [\[233\]](#) (helium nuclei) with a total energy of 17 MeV. Redirecting these magnetically or electrically would give us a reaction jet velocity of 20,000 km/s or a specific impulse of roughly 2 million seconds. With one ton of fuel, your ten-ton family spaceship can accelerate at one G for two days. (You could also do this with transuranic fission, but then your exhaust jet is composed of really nasty stuff instead of helium.) This makes all the difference in exploring the Solar System. A Hohmann transfer orbit to Mars, the minimum-energy path that is essentially all that our chemical rockets can manage, takes 9 months, and a launch window only happens every 26 months. [\[234\]](#) This is clearly unworkable as a basis for commerce. Nuclear rockets, of whatever type, make it possible to fly high-energy low-time trajectories.

Mars varies from 50 to 350 Gm (gigameters, i.e. million kilometers—one AU is 150 Gm) from Earth, depending on where they are in their orbits. Accelerating at 1 gravity for one day puts you 50 Gm out and travelling at 3.6 Gm per hour. As a point of reference, Earth and Mars move in their orbits on the order of 0.1 Gm per hour, so for a typical trip, you accelerate one day, coast a few days, and decelerate one day. Your orbit is pretty close to a straight line. Just watch out where you point that exhaust jet.

Ad Astra per Koken

*Do I dare
Disturb the universe?*

—T. S. Eliot



A classic 1920's-era Koken barber chair weighs about 250 pounds. It is a solid piece of old-fashioned machinery; many original ones are still in use today. Chairs like that were also something of a luxury item: the Titanic had two of them in its first-class-only barber shop, as did many top ocean liners of the day. But nobody in his right mind would design a *spacecraft* with a barber chair in it!

Well, nobody except Ted Taylor. Taylor was an interesting figure in technological history: as a nuclear engineer, he designed both the smallest and the largest fission devices the United States ever built. [\[235\]](#) Taylor's insistence that there be a barber chair in his spaceship was an in-your-face way of saying that this was a ship, like an ocean liner, and not a dinky little capsule stuck on top of a skyrocket.

Taylor's ship, of course, was the Orion Project, the very first study funded by ARPA, the now-famous research arm of the DOD (and the second major project of General Atomics, after the TRIGA reactor). They started studying

Orion in earnest in 1959. It was a serious engineering effort, with some of the country's top minds (besides Taylor, most famously Freeman Dyson). Some of the design is still classified Top Secret.

That is because Orion was a spaceship what would be propelled by a string of A-bombs set off behind it. The idea sprang from a nuclear-weapon test in the mid-50s in which some metal spheres covered in graphite had been set up just 50 feet away from the bomb. They were later discovered to have been blown quite a distance, but essentially unharmed. Stanislaw Ulam, one of the brightest minds at Los Alamos—he was co-inventor of the hydrogen bomb with Edward Teller and contributed a key element to John von Neumann's theory of self-reproducing machines, among many other things—was captivated by the notion that nuclear explosions could be used to drive a vehicle. Taylor caught the bug, and was picked to head the project. The reference Orion design was 150 feet in diameter and 4000 tons. Tons. You could afford to put a barber chair in that. You could afford to build it of steel with ship-building techniques. And it was, as far as a team of top technical talent could determine, feasible with the technology of 1960. The scientists seriously expected to be visiting the moons of Saturn by the 1970s. *It was a possibility.*

On the other hand, there is always the far end of the Orion research: the super-Orion propelled by hydrogen fusion bombs instead of small fission ones. Dyson wrote,

... A ship with a million-ton payload could escape from the Earth with the expenditure of about a thousand H-bombs with yields of a few megatons. The fuel cost of such a mission would be about 5 cents per pound of payload at present prices. Each bomb would be surrounded by a thousand tons of inert propellant material, and it would be easy to load this material with boron to such an extent that practically no neutrons escape to the atmosphere. The atmospheric contamination would only arise from tritium and from fission products. Preliminary studies indicate that the tritium contamination from such a series of high-yield explosions would not approach biologically significant levels.

They estimated that the biggest ship they could get off the ground would be about 8 million tons. For comparison, a modern high-end cruise ship grosses 126,000 tons and carries 3000 people. [\[236\]](#) An 8 million ton ship could carry something like 200,000 people, in similar luxury.

One key fact about the Orion technology was that the total atmospheric contamination for a launch was roughly the same no matter what size the ship; so that there would be an impetus toward larger ones.

From 1950's *When Worlds Collide* to the recent Neal Stephenson *Seveneves*, one of the staples of science fiction is the end-of-the-world story where people struggle to launch a remnant of humanity into space to escape the destruction of the planet. With the mega-Orion, should we be forced to such an extreme, we could save the entire human population with 35,000 launches. For comparison, there are 100,000 airliner flights *every day* worldwide.

Orion ultimately foundered on not having a strong mentor in Washington politics, and fallout fears. These had led to the atmospheric test bans, which would prohibit any Orion launch.

It is quite possible to engineer bomb/propellant packages that are considerably cleaner than the bombs used in WWII or tested in the Fifties, and for the really big ships note that fusion is a lot cleaner than fission per unit energy released. But it isn't possible to remove radiation completely. If it is true that any amount of radiation, however small, causes some risk multiplied by the number of people exposed, atmospheric detonations, no matter how remote, will always come with a statistical expected excess cancer rate. So the LNT, the Linear No Threshold hypothesis, makes a huge difference in calculating risk for a radiation-producing enterprise such as the Orion.

Linear hypotheses abound in science, and in plenty of cases it is understood that the phenomenon is non-linear but a linear approximation is used anyway. One reason is this makes calculation enormously easier. Freeman Dyson, who did the fallout mortality analysis for Project Orion, calculated that you would get 10 excess cancer deaths per launch, explicitly using the linear hypothesis with a figure of one death per 10,000 rem (100 Sv) however distributed. [\[237\]](#) Of course, what this means, even with the linear hypothesis, is that from the world population of 7.6 billion, 497,040,010 people would die of cancer in the years [\[238\]](#) following an Orion launch

instead of the 497,040,000 who would normally be expected to. But it also means that the calculated dose per person was 0.02 millirem (0.2 microSieverts)—in a world where natural background exposure is about 300 millirem. And remember that the likely protracted no-damage threshold is 50,000 millirem. See Appendix D.

Only an extremely doctrinaire adherence to the almost certainly false LNT hypothesis could hold this out as a problem. Yet not only is the hypothesis received wisdom in regulatory circles, but it has been virtually impossible even to allow the question to be studied. This is yet another social pathology holding us back from technological progress; Orion aside, outer space is a high-radiation environment. We will never inherit the universe until we learn how to live with radiation—and that means studying it honestly.

It's Goddamned radioactive out there.

—Larry Niven, *Neutron Star*

——Bottom Line——

Earth is the cradle of humanity, but one cannot remain in the cradle forever.

—Konstantin Tsiolkovsky

New ideas are controversial when they challenge orthodoxy, but orthodoxy changes with time, often surprisingly fast. It is orthodox, for example, to believe that Earth is the only practical habitat for Man, and that the human race is close to its ultimate size limits. But I believe we have now reached the point where we can, if we so choose, build new habitats far more comfortable, productive and attractive than is most of Earth.

—Gerard O'Neill (1974)

The young Isaac Asimov, growing up in New York City, imagined as the capital of the Galactic Empire a city which covered an entire planet. Compare the beautiful, cool green hills of Earth—excuse me, of my home in northern Pennsylvania—to the flat, hot, crowded concrete wastelands of LA or New York. In 1000 years, a relative eyeblink geologically speaking, if human development continues the way it has for the past 10,000, the whole Earth will be like LA. The only animal life left will be zoos, farms, and pets—and with nanotech food production, there won't even be any farms.

This is a consummation devoutly not to be wished. We have to control the population. It's not a question of if, but when.

... and, of course, how.

The problems are these: Outside of the Four Horsemen of the Apocalypse, the only known way to moderate population growth is wealth. (Note that even in China, the birth restrictions are part of an implicit social contract that includes a meteoritic rise in the average income, and even so are in the process of being phased out.) The technophobic proscriptions of green fundamentalism are deeply anti-wealth, and thus ultimately self-defeating,

as any reduction in individual eco-footprints will be swamped by more footprints. As no less a Whole-Earther than Stewart Brand himself points out, “subsistence farming is an ecological nightmare.”

What then are we to do with the previously-poverty-stricken billions? Are we going to have to pave over the Earth after all? I can see but one solution that really works, in the long run: get them off the Earth. And by them of course I mean us all, or all but a few percent.

About 10,000 times as much energy as we actually use today, 10^{17} vs 10^{13} watts, falls on the earth as sunlight. But 10 billion times more than that floods through the solar system, available for the taking by anyone who is out there—and energy is the basis of wealth. There are at least tens of thousands of times more usable matter in the asteroids as here—not even counting the other planets! There is plenty of room and resources for hundreds of billions of very wealthy humans without using the Earth at all—we can afford to set Earth aside as a natural preserve or managed park or whatever combination we like.

With a large, wealthy, off-world population we can afford to experiment. We can experiment with different ecologies and governmental arrangements in the various space colonies. We can experiment with the Earth’s climate and ecology (which we are already doing, of course!) but have the resources to fix it if we screw up, and not place the human race in danger of extinction with every stupid blunder of World Weather Control. We can afford not to fight over the Earth’s resources, because they’ll be 1% of 1% of what’s available.

The human body is reasonably well adapted for life on the surface of the Earth—the part that is land not covered by ice. But even here we need clothing and shelter for large parts of the planet, for large parts of the year. In becoming the most widely distributed animal, we mediate between our bodies and our environment with our inventions. It was always assumed in classic SF that the same process would continue in more sophisticated form on the moon, on Mars, and throughout the solar system. It’s fairly easy to envision how nanotech will contribute to that process; in fact, it seems likely that nanotech will be the defining level of capability that makes widespread space colonization feasible. In space, we must replace the entire

capability of the biosphere to rearrange atoms, and provide the energy necessary to do it.

Less common in SF was the extensive modification or complete replacement of the human body itself. One obvious reason is that science fiction needs to provide characters with whom the reader can identify, and this gets harder to do as people become less human. As long as the modifications are medical or genetic, providing radiation resistance or gills for example, there is no narrative problem. Classic SF was full of anti-aging, mechanical education, and similar enhancements.

One of the more amazing things about the space-colony movement of the 70s and 80s was that it would actually have been possible to build earth-like habitats in orbit with the technology of the 20th century. On the other hand, it would also almost certainly have been much more expensive to do so than the enthusiasts realized. Space colonization is much more likely to succeed when it isn't necessary to recreate a large-scale earth-like environment for unmodified biological humans to live in.

Furthermore, spacesuits in current technology are cumbersome and uncomfortable. We should wish for the vast majority of humans living in the vast majority of the universe that they should be adapted to their environments, that it should feel just as good, not only physically but psychologically, to stand on the Moon as it is for us to walk along the seashore on a warm spring day.

One of the major historical watersheds we can expect from the technology reasonably foreseeable in the next half-century or so is the ability to build replacement body parts that actually work better than the original. From peg-legs to hooks, this has never been the case before. The coming century will be the century of enhancement. The human of the future will have more and better senses, be stronger and be adaptable to a much wider range of environments, and last but not least have the biosphere atom-rearranging capability built in. The human of the future need not have any ecological footprint at all.

Furthermore, the human society of the future desperately needs a frontier. Without an external challenge, we degenerate into squabbling, self-deceiving, Eloi Agonistes. But the Solar System is a foeman worthy of our steel; and after that, the galaxy is even more so. We can pit ourselves against the universe instead of each other for a long, long time.

We can, that is, if we try. *It is a possibility.*

All civilizations become either space-faring or extinct.

—Carl Sagan

We who were meant to roam the stars go now on foot upon a ravaged earth. But above us those other worlds still hang, and still they beckon. And so is the promise still given. If we make not the mistakes of the Old Ones then shall we know in time more than the winds of this earth and the trails of this earth.

—Andre Norton, *Star Man's Son*

Ask ten different scientists about the environment, population control, genetics, and you'll get ten different answers. But there's one thing every scientist on the planet agrees on. Whether it happens in a hundred years or a thousand years or a million years, eventually our Sun will grow cold and go out. When that happens, it won't just take us. It'll take Marilyn Monroe, and Lao-Tzu, and Einstein, and Morobuto, and Buddy Holly, and Aristophanes, and all of this...all of this...was for nothing. Unless we go to the stars.

—Babylon 5

Rest enough for the individual man. Too much of it and too soon, and we call it death. But for Man no rest and no ending. He must go on—conquest beyond conquest. This little planet and its winds and ways, and all the laws of mind and matter that restrain him. Then all the planets about him, and at last out across immensity to the stars. And when he has conquered all the deeps of space and all the mysteries of time—still he will be beginning.

—H. G. Wells, *Things to Come*

She turned to stare at him, slowly shook her head. He heard someone shouting, but then a trumpet started softly, introducing a new number.

Martha sucked in a hurt breath, pressed her hands together, and hurried from the room.

“It’s too late,” he said after her.

Her footsteps stopped on the stairs. The trumpet was alone. Donegal listened; and there was no babble of voices, and the rest of the orchestra was silent. Only the trumpet sang—and it puzzled him, hearing the same slow bugle-notes of the call played at the lowering of the colors.

The trumpet stopped suddenly. Then he knew it had been for him. A brief hush—then thunder came from the blast-station two miles to the west. First the low reverberation, rattling the windows, then the rising growl as the sleek beast knifed skyward on a column of blue-white hell. It grew and grew until it drowned the distant traffic sounds and dominated the silence outside.

—Walter M. Miller, Jr., *Death of a Spaceman*

20 To Singularity, and Beyond

“In two hundred years, there won’t be any Terran Federation. The Government will collapse, slowly. The Space Navy will disintegrate. Planets and systems will lose touch with Terra and with one another. You know what it was like here, just before the War? It will be like that on every planet, even on Terra. Just a slow crumbling, till everything is gone; then every planet will start sliding back, in isolation, into barbarism.”

—H. Beam Piper, *The Cosmic Computer*

A dark age is not when you’ve forgotten how to do something. It’s when you’ve forgotten that you could.

—David Altrogge

This passage from John W. Campbell’s classic SF short story *Twilight*, even though it was written in 1934, has an eerie ring to it when one considers the gap between what we and our technology are capable of today and what we actually accomplish with it:

But as I stepped from that ship and watched it rise away from me, I saw why the race of man was dying. I looked back at the faces of those men, and on them I read the answer. ...

For the one thing that had made man great had left him. As I looked in their faces and eyes on landing I knew it. They looked at me, interested at this rather unusual-looking stranger—and went on. They had come to see the arrival of a ship. A rare event, you see. But they were merely welcoming me in a friendly fashion. They were not curious! Man had lost the instinct of curiosity.

Oh, not entirely! They wondered at the machines, they wondered at the stars. But they did nothing about it. It was not wholly lost to them yet, but nearly. It was dying. In the six short months I stayed with them, I learned more than they had learned in the two or even three thousand

years they had lived among the machines.

Can you appreciate the crushing hopelessness it brought to me? I, who love science, who see in it, or have seen in it, the salvation, the raising of mankind—to see those wondrous machines, of man's triumphant maturity, forgotten and misunderstood. The wondrous, perfect machines that tended, protected, and cared for those gentle, kindly people who had—forgotten.

They were lost among it. The city was a magnificent ruin to them, a thing that rose stupendous about them. Something not understood, a thing that was of the nature of the world. It was. It had not been made; it simply was. Just as the mountains and the deserts and the waters of the seas.

You imagine that the same feeling in the European peasants among the ruins of the Roman Empire, or the Chinese peasants among the ruins of the Qing dynasty. There was a wistful irony when Eugene Cernan said, “The U.S. desperately needs to do something to recapture the pioneering spirit that allowed it go to the Moon.” Cernan was the bearer of a sad distinction: he was the last man to set foot on the moon. And now he is gone, and soon there will be no one alive who has trod on any world but Earth. Not too long after, those of us who can remember watching it will be gone as well; and soon we as a people will have forgotten that we could.

Campbell picked up the idea of the Eloi from Wells' *The Time Machine*, one assumes, but stripped the extraneous elements and turned it into the focused story of fallen grandeur that made *Twilight* one of the classic stories of Golden Age SF. He then turned around, and as editor, inspired the young Isaac Asimov to turn the same premise—essentially the fall of the Roman Empire—into the *Foundation* trilogy. [\[239\]](#) This time the empire spans a whole galaxy, a setting which became a staple for later science fiction. But the fall always happens. Empires contain the seeds of their own destruction. Do they really? After all, *Götterdämmerung* (“Twilight of the Gods”) is an archetypal literary setting and its narrative advantages are not lost on science fiction writers. On the other hand, all actual historical human empires have collapsed: two of them, the British and the Soviet, within my own lifetime. Is the American one merely following an predestined tragic trajectory? Of the two classic historians who are most known for addressing

the question, Spengler thought the cycle was deterministic, whereas Toynbee believed that while civilizations commonly did fall, they could sometimes meet a challenge and grow to overcome it.

One of the reasons to think we might be in a twilight is that many of the phenomena we speculated on as possible causes for stagnation can be seen operating in civilizations on the wane: fierce new religions that displace the stable older ones; advancing social ossification and sclerosis from bureaucracy; entrenched interests blocking innovation and progress; and cultural decadence enervating the entrepreneurial spirit of a people.

Perhaps such a process of ineluctable entropy might be better viewed from the opposite perspective: a reversion to the mean. After all, it is not the usual state of humanity to live at the height of a glorious empire, but to live in comparative squalor at the edge of subsistence. The fact needing explanation is not the collapse but the rise; not why we don't have flying cars but how we ever got cars. The famous Heinlein "bad luck" quip is a tongue-in-cheek rendition of Toynbee's theory of the "creative minority." Wells' *Things To Come*, book and movie, predicted an end to the old international order due to a protracted war that destroyed civilization. For once he was behind the times. World War I had already done that. The *Pax Britannica* had been the most important formative influence on the character of the 19th century. That came to an end with a bang in World War One, and the costs of World War Two essentially bankrupted Great Britain. By the death of Winston Churchill in 1965, the sun had set on the British Empire. The cause of the *Pax*, Britain's edge in weaponry (e.g. machine guns) and transportation (railroads and steamboats) that were her legacy from the Industrial Revolution, dissipated as the rest of the European nations (and the US) caught up.

The American experiment can be viewed as the real-world example, perhaps the model, for Wells' *Things to Come* and its legacy in science fiction, including everything from Asimov's *Foundation* to Rand's *Atlas Shrugged*. The old, sclerotic civilization is committed to its own destruction; a cadre of enlightened airmen or academics or industrialists departs to a redoubt and forms a new world in embryo, preserving all the knowledge and virtues of the old but discarding the social pathologies. It is tempting to see America as the redoubt, the European *Ancien régime* as the old, sclerotic civilization, and the story as vindicated.

*The candle flame gutters. Its little pool pool of light trembles.
Darkness Gathers. The demons begin to stir.*

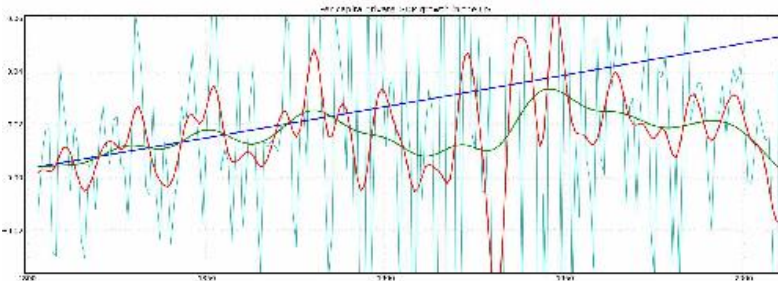
—Sagan, *Demon-Haunted World*

*Far-call'd, our navies melt away;
On dune and headland sinks the fire.
Lo, all our pomp of yesterday
Is one with Nineveh and Tyre.*

—Rudyard Kipling

*We have convinced ourselves (if there is any virtue in this Study) that
the destruction which has overtaken a number of civilizations in the
past has never been the work of any external agency, but has always
been in the nature of an act of suicide.*

—Toynbee, *A Study of History*



*Per capita GDP growth rates in the US (sans government spending),
with two smoothings to illustrate medium and longer-term trends. (As
centered moving averages, the smoothings will appear to anticipate
future trends.) The straight blue line is a linear fit to the 19th century
only.*

Here is, if you will, the economic history of the US in a nutshell. The first point to note is that, Great Stagnation and all, growth was still positive in the latter 20th century. We're still getting richer, just not as fast as before. We are very rich, and very lucky, compared to the average human any time, anywhere. We really are the Eloi.

The other point is an interpretation of that graph. Many people who write about a technological “singularity” sometime in the coming century, expect it to be associated with accelerating growth. The question is why growth doesn’t seem to be accelerating to a takeoff mode now, if that is going to happen? My interpretation of the graph is that it should be, and that in fact it did in the 19th century. Actual growth rates, smoothed, match the blue regression line quite well before about 1900.

In most forms of evolution, specifically including biological life, the process is an accelerating one. The more you learn, the better you learn to learn, and known techniques feed on one another to form a growing ability to do anything. That was clearly true of the US economy before the Progressive Era. Improving communications and transportation, railroads and telegraph, made it easier and faster to build a new business, put any new invention to use, connect producers and customers.

Industrial regulation began in 1887 with the ICC, and continued in the early 20th century with a series of price control measures on railroad travel—the economic equivalent of applying a tourniquet to the patient’s neck. Then with the railroads on the edge of collapse in the face of the needs of WWI, President Wilson simply nationalized them. “During the Progressive Era, ... the scale and scope of government regulations grew dramatically.” [\[240\]](#)

The Progressive Era also gave us income taxes, eugenics, the Federal Reserve, the FTC, the FDA, the AF of L, anti-trust, and Prohibition.

My interpretation of the growth graph is that throughout the 19th century, innovation was allowed to happen, and growth accelerated. In the 20th, especially in the Great Stagnation era, many innovations were stifled, notably in transportation. Transport costs quit tumbling. Anything dependent on energy growth starved. The tires of the economy developed a leak and are slowly going flat.

We aren’t getting richer as fast as before, and absolutely nowhere near as fast as we would have done had innovation not been strangled. We are about 3 times as rich as we were in 1960 in constant dollars. If we had stayed on the accelerating growth curve, we would be instead 12 times as rich, and many of us could be flying jet-powered cars. In the postwar period we very nearly regained the accelerating growth curve, and SF writers and futurists were at least not completely crazy to imagine we might be able to stay on it. If we could have done, we would have been 130 times richer in

2062 than 1962. And yes, the average working man could very well have owned a private jet.

For more than three decades, macroeconomics has gone backwards. ... A parallel with string theory from physics hints at a general failure mode of science that is triggered when respect for highly regarded leaders evolves into a deference to authority that displaces objective fact from its position as the ultimate determinant of scientific truth.

—Paul Romer

[L]et me tell you about a dirty little secret of economics —namely, that we don't know very much about how to raise the long-run rate of economic growth.

—Paul Krugman

If economists could manage to get themselves thought of as humble, competent people, on a level with dentists, that would be splendid!

—John Maynard Keynes

Asymptotes

Ray Solomonoff produced arguably the first formal model of an increase in processing power leading to a mathematical singularity of intellectual capacity. [\[241\]](#) This predicted an asymptotic rise at a date that depended on various model parameters, and very likely was influential in the adoption of the name “Singularity” for the concept.

The intuition for such a hyperbolic growth curve is straightforward.

Suppose that technological progress can be parceled into a series of fixed-size problems. The solution of each can be done with some fixed number of machine operations. Current progress, with roughly a fixed number of human minds (and thus a linear rate of problems solved), appears capable of inducing an exponential improvement rate in computing hardware (measured in operations per dollar). The rate is usually measured in time, but in the model, could just as well be measured in (the linearly related) total number of problems solved. This hypothesis is equivalent to saying that it is possible to have a constant growth rate on a *per capita* chart like the “nutshell” one above.

Once we can obtain, for an affordable outlay, problem-solving capability in AI form of total overall ability comparable to the current technical community, the dynamic changes. If we double the brains available, we halve the time to solve the next problem in our list. Since we’re measuring computational improvement in problems solved, the next generation of computers is available in half the time, and (again for a fixed cost) we can redouble our problem-solving ability. Thus the next set of problems is solved in one quarter the original time, and the next in one eighth, and so forth, providing us the solution of an infinite series of problems in a finite time.

As Solomonoff hastens to point out,

Usually, when infinities like this one occur in science, they indicate a breakdown of the validity of the equations as we approach the infinity point.

He proceeds to speculate that the breakdown in this case would be the end of the Moore's Law computational improvement. In practice, it could be any of a vast number of things. Computational speedup is only one of the many feedback loops in the improvement of technology as a whole. Most of these have to go through various physical processes (starting with building the capital equipment which fabricates microchips, but including such mundane necessities as the transportation of raw materials and finished machines). Any one of these would form a bottleneck if the rest were significantly accelerated.

There is a second, perhaps more subtle problem with a hyperbolic model. As the problem-solving intervals decrease exponentially in duration, causing an asymptotic increase in problems solved, they also cause an asymptotic increase in the fixed-per-interval expenditure for machinery. In other words, the model consumes an infinite amount of physical resources (and money) in finite time, as well.

We can form a more realistic model of the self-improvement process by investigating a sector where Moore's Law is strongly active already, namely the semiconductor industry.

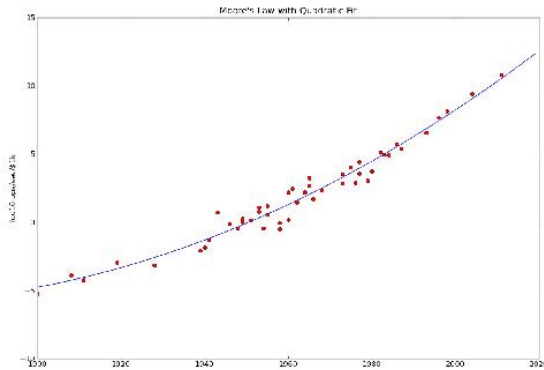
Moore's Law

Consider the (US) semiconductor industry over the past 15 or so years, where a measurable Moore's Law has been operating. Notably, in this period, design automation has contributed enormously to the ability of mere human beings to design the staggeringly complex microprocessors and other components that make up current-day computers. This ranges from architecture to electronic phenomena to geometric design of chip masks to allow for refraction effects of the UV light used to expose the chips under construction.

Thus feedback from increasing processing power and software sophistication in semiconductor manufacture is an excellent proxy for the kind of increased smarts to be expected in an AI takeoff, and in a sector with nicely measurable results. Furthermore, for the past 15 years, the industry (in the US [\[242\]](#)) has been remarkably stable: it can be considered statistically to have a constant annual output value of \$75 billion, spending \$15 billion on raw material, \$8.25 billion on capital equipment, and \$12.75

billion on research and development. [243] The number of production workers has been more or less even over the period at about 85 thousand, but the number of non-production workers has shrunk from 93 thousand in 1997 to 62 thousand in 2007.

Meanwhile the performance of the product has been increasing at a faster-than-exponential rate:



Moore's Law with a quadratic growth-rate fit, from Kurzweil's and the author's data. [244]

Given that the raw material input to the industry is essentially constant and the dollar value is constant, the curve can be taken to represent the intelligence with which the atoms of raw materials are rearranged into products; a relatively pure measure of innovation. Thus the semiconductor industry as a whole manages this accelerating improvement from a fixed 28% reinvestment rate.

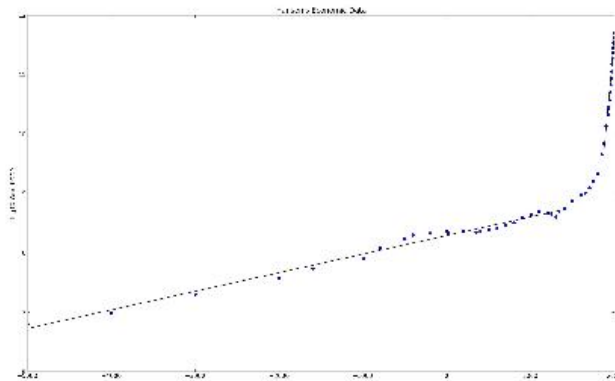
According to the curve, cost of computation has dropped by a factor of 152,000 since 1985. The net present value of a human engineer of the sort participating in the semiconductor industry is about \$1 million. The amount of computation necessary to host an AI at a human level costs probably just about that, just about now.

A Series of Growth Modes

Economist Robin Hanson analyzes the economic history of the human race as a series of distinct changes in the growth rate. At least two major accelerations can be identified. The growth rate for humanity's gross output

jumped by about a factor of 250 with agriculture, and by a factor of 60 with the Industrial Revolution.

The fact that the Moore's Law growth rate is changing lends credence to a proposition that it might be in the process of shifting from one mode to another.



Hanson's data for agrarian and industrial growth modes, with the Renaissance / Industrial Revolution knee between.

Hanson speculates that the next jump in the series, assuming the pattern holds, might well occur within the coming century: the industrial economy has seen roughly as many doubling times as the agrarian period did.

We find the analysis of historical growth as a series of growth modes with intervening phase changes to be compelling, but the endogenous model in which phase changes are precipitated simply by the number of doubling times from a previous one to be little short of numerology. Let us advance an alternative theory.

What Technology Wants

Von Neumann hypothesized what he called the “complexity barrier:”

There is thus this completely decisive property of complexity, that there exists a critical size below which the process of synthesis is degenerative, but above which the phenomenon of synthesis, if properly arranged, can become explosive, in other words, where syntheses of automata can proceed in such a manner that each

automaton will produce other automata which are more complex and of higher potentialities than itself.

Three recent studies of the phenomenon of technological progress in human communities, Kevin Kelly's *What Technology Wants*, Steven Johnson's *Where Ideas Come From*, and Matt Ridley's *The Rational Optimist*, give credence to von Neumann's concept of the complexity barrier.

Technological progress in human societies depends on the complexity—size and network effects—of the economic and intellectual community within which economic and intellectual intercourse are possible. Isolated societies, even though composed of people just as industrious and intelligent as the larger ones, tend to regress and lose technologies instead of progressing and inventing new ones. Aboriginal Tasmania is a classic example of this phenomenon. There seems to be some point of complexity above which a society is self-improving, and below which it is not.

All of these analyses, Kelly's in particular, invoke the notion that at any particular state of knowledge, there is a certain set of inventions available to be discovered as the next step. Thus in some sense, technological creativity is analogous to explorers in a landscape following valleys and mountain passes; the directions they take are determined by the landscape rather than their internal compasses. There is a sort of boundary or frontier. Visionary geniuses who are ahead of their time—da Vinci, Babbage, Feynman, and Drexler spring to mind—find their ideas impossible to implement. Ideas on the frontier of the technium, to use Kelly's term for the corpus of technical knowledge at a given time, tends to be independently and simultaneously reinvented. While Kelly gives plenty of examples, there is a particularly interesting one from science fiction: In 1992, three different SF books came out based on the then novel idea that there could be computer viruses which could infect human minds (or vice versa). And for just that extra self-referential touch, all three books I mentioned in the previous paragraph were published in 2010.

Space Mining

Let us re-interpret Hanson's model of growth-rate phase changes. Instead of some internal dynamic in the technium producing a phase change after

some number of doubling times, the roughly regular progression of phase shifts can be better explained as a result of the terrain in the idea-space through which the technium is expanding. A fractal distribution of “fertile valleys” —of volumes of idea-space affording rapid growth and high productivity—would account for the overall shape of the series of growth phase changes. The timing and other parameters, however, would depend on particulars of the terrain and could not be predicted in detail from the preceding series. Valleys would occur randomly with a frequency inversely proportional to their sizes. This is called a Zipf’s Law distribution (and other names depending on the particular field) and describes a wide variety of phenomena in nature, from words in language to mountains.

On this view, the technium is an expanding volume in an idea space of high (and indeed increasing) dimensionality. When it contacts a valley, expansion into the valley proceeds at a higher-than-normal rate, producing the super-exponential growth characteristic of a phase shift. Once the valley is saturated, growth reverts to the simple exponential but at a higher rate due to the increased size and dimensionality of the frontier. This notion has some similarities to the theories of punctuated equilibria in biological evolution.

For example, a very early technium consisting of fire, clothing, crude shelter, and chipped flint tools—the “Mousterian toolkit” —vastly expanded the inventory of geographical locations in which humans could live. This afforded a higher population growth rate than a steady-state existence in clement climes. In this case the entropy increase in the accessible space was very literally determined by the actual physical terrain.

While it is perilous to generalize, it is possible to discern a pattern to the phase changes, which we hope tells us something about the typical forms of the terrain. Arguably, each phase change in physical capability is accompanied by (and somewhat preceded by) a corresponding increase in informational capability:

Informational development	physical development
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Manual dexterity	Mousterian toolkit
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Language	Agriculture
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Writing	Civilization
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Printing press, science	Industrial Revolution
Internet, AI	nanotech, robots

One striking aspect of the list is that each stage involved mastery of some self-replicating phenomenon: fire, crops, ideas, machine tools, and, we presume, ultimately programs.

It is difficult to attribute growth rates to many of these phenomena, but the penultimate pair has a compelling symmetry: with the introduction of the printing press and the acceptance of the scientific method, scientific publication shifted from a growth mode essentially the same as the existing overall economic one of about 0.1% to about 5%. Within a few centuries—very quickly on the timescales under discussion—physical economic output shifted into a 5% growth-rate mode.

We can speculate that the core of an idea-space valley affording a given growth mode is surrounded by a halo, which the frontier of the technium reaches first, of techniques by which information can be handled in the growth mode. The obvious inference is that current Moore's Law information technology growth will be completed by a revolution in physical capability that brings the rest of the economy up to a Moore's Law-like growth rate. We cannot say where this will stabilize; Moore's Law over the period of the chart has averaged about 40% per annum.

——Bottom Line——

The single most important determiner of the economic growth rate is the productivity of capital: how long it takes a given unit of capital to produce an equivalent unit of product, or new capital. In current technology, on the average, this is about 15 years, for a growth rate of 5%.

Moore's original observation had to do with shrinking transistors, making them not only more numerous and cheaper but faster as well. The same phenomenon holds for physical devices: nanotech could operate at megahertz mechanical frequencies, thousands of times faster than current machines at capital-replication tasks. Translating this into an actual economic growth rate involves understanding where all the bottlenecks are and how much they can be widened.

Explanations for the Great Stagnation can come in two flavors. The default one seems to have been that the technium has, since the 70s, been expanding across a barren high desert, except for the fertile valley of information technology. I began this investigation believing that to be a likely explanation. But I have come to the conclusion that that is wrong. As the technium expanded, we have passed many fertile Gardens of Eden, but there has always been an angel with a flaming sword guarding against our access in the name of some religion or social movement, or simply bureaucracies barring entry in the name of safety or, most insanelly, not allowing people to make money.

Perhaps a better metaphor would be that the fertile valleys have been dammed up against the encroachment of the rising waters of the technium. On that view, there are more and more viable passes into the valley as the technological level rises. Sometimes that takes the form of a technological end run, as in the current drone revolution. Sometimes it simply involves someone escaping the ban, as in the *Things to Come* / *Foundation* trope and the American experiment. Or if the sclerotic polity is but one of many, the rest of the world will simply leave it behind, as happened to Shogun-era Japan. Sometimes the political winds shift, as has happened in modern-day China. But in every case, the farther the technium rises, the less secure the empty valley becomes.

The “Singularity” might best be thought of as the second half of the information technology revolution, extending it to most physical and intellectual work. Overall economic growth rates could shift from their current levels of roughly 5% to Moore’s Law-like rates of 40%.
What would our technology look like then?

FUTURE, n. That period of time in which our affairs prosper, our friends are true and our happiness is assured.

—Ambrose Bierce, *The Devil’s Dictionary*

21 The Second Atomic Age

Impossibilities no longer stood in the way. One's life had fattened on impossibilities. Before the boy was six years old, he had seen four impossibilities made actual—the ocean-steamer, the railway, the electric telegraph, and the Daguerreotype; nor could he ever learn which of the four had most hurried others to come. He had seen the coal-output of the United States grow from nothing to three hundred million tons or more. What was far more serious, he had seen the number of minds, engaged in pursuing force—the truest measure of its attraction—increase from a few scores or hundreds, in 1838, to many thousands in 1905, trained to sharpness never before reached, and armed with instruments amounting to new senses of indefinite power and accuracy, while they chased force into hiding-places where Nature herself had never known it to be, making analyses that contradicted being, and syntheses that endangered the elements.

—Henry Adams

Nuclear energy is incomparably greater than the molecular energy which we use today. If the hydrogen atoms in a pound of water could be prevailed upon to combine together and form helium, they would suffice to drive a thousand-horsepower engine for a whole year. The discovery and control of such sources of power would cause changes in human affairs incomparably greater than those produced by the steam-engine four generations ago. Schemes of cosmic magnitude would become feasible. Geography and climate would obey our orders.

Communications and transport by land, water and air would take unimaginable forms, if, as is in principle possible, we could make an engine of 600 horse-power, weighing 20 lb and carrying fuel for a thousand hours in a tank the size of a fountain-pen. Wireless telephones and television, following naturally upon their present path of development, would enable their owner to connect up with any room similarly installed, and hear and take part in the conversation as well

as if he put his head in through the window. The congregation of men in cities would become superfluous.

—Winston Churchill, *Thoughts and Adventures* (1932)

Confluence

You boys like to call this the pushbutton age. It isn't, not yet. Not until we can team up atomic energy with electronics. Then we'll have the horses as well as the cart.

—“Dr. Cal Meacham” in *This Island Earth*

The true renaissance of nuclear power, capable of delivering on its promise of cheap, clean, virtually limitless energy, will come when we get to the real Atomic Age—the age of atomically precise machinery as in nanotech. There are three major ways in which nanotech enables broadly based nuclear technology.

First and most obvious is isotopic separation. Isotopes are nuclei with the same number of protons, but different numbers of neutrons. Because they have the same charge, the electronic structure they impose on an atom is the same; chemically, they are the same element. That makes them extremely difficult to separate with conventional chemical techniques.

But because the number of neutrons is different, their properties in nuclear processes are as different as different elements are chemically. Famously, U235 is fissile but U238 is not. More esoterically, Xenon-134 is essentially stable, with a half-life of 58 billion trillion years, and a thermal neutron cross section of just 0.26 barns, while Xenon-135 is vigorously radioactive, with a half-life of 9 hours, and a cross section of 2.6 million barns. There are many examples where a particular isotope is much more useful than another in nuclear design. So in nuclear engineering, isotopic makeup is important throughout the mechanism, not just in the fuel. Separation is expensive with current bulk technology, but could be much cheaper with nanotech, which will build everything atom by atom anyway. If your machines can handle an atom at a time, you simply sort them by weight, or nuclear magnetic properties. This is not to say it would be simple or straightforward: at that scale, a radioactive atom is a bomb that will randomly go off and wreck your machinery! But nanotech gives you the basic tools to apply lots of ingenuity to the problem at the right scale.

Isotopic separation is far too expensive in current technology to be used merely to clean up stuff that has been exposed to neutrons—“low-level nuclear waste”—but with nanotech that would be straightforward. This is the capability that makes nuclear into a clean, contained, technology.

The second big advantage will be the ability of nanotech to build extreme or precise structures in the target nuclear mechanism itself. We would still be nowhere close to manipulating the nucleus; the size of the nucleus relative to the atom is about that of a golf ball sitting on the fifty-yard line relative to the whole football stadium. But you have a lot more control over what nuclei are present, and in what relation to each other at the atomic scale, and are likely to be able to build structures that provide intense electric and magnetic fields that can influence nuclear reactions.

It turns out that a working moderated reactor can be built using just 25 grams, less than an ounce, of Californium-251. [\[245\]](#) But Cf251 is a purely synthetic element, today only produced in reactors in microgram quantities. It would take an extensive nuclear industry where it was produced in quantity *and* an inexpensive separation ability to make very small reactors using it viable. The main problem with using current methods for transmutation is that the main technique we have for changing one isotope into another is bombarding it with neutrons. But when we are trying to produce an isotope that is highly reactive to neutrons, the product nuclei are much more likely to be ruined by a given exposure than the precursor is to be properly treated. So bulk technology is simply incapable of doing a lot of the nuclear processing that we could do in theory if we could handle atoms individually.

The third advantage is simply the immense productive power of nanotech. You can imagine having your machine under continuous reconstruction, with the entire mechanism replaced with new parts every day. This cuts down considerably on the build-up of defects due to radiation, for example. (That is essentially the way *Deinococcus radiodurans*, the remarkably radiation-resistant “Conan the Bacterium,” works.) Cell repair machines would make us considerably less vulnerable to the health effects of radiation—something we are going to have to have anyway if we are going to live in space.

On the flip side, without nuclear energy nanotech is drastically underpowered. Typical piston engines produce less than a horsepower per

pound of engine weight. Gas turbines produce 2.8 at private airplane turboprop size and 5.8 in the GE90 airliner engine. Modern rare-earth electric motors are in the same ballpark. But a Drexler electric motor, as mentioned in chapter 4, would produce about 3 billion horsepower per pound. Nuclear power densities and nanotech power needs are roughly matched, like chemical fuels and steel machines.

If you had given Newcomen, *ca.* 1700, a tank full of gasoline, the best he would have been able to do with it would have been to burn his new steam engine down, or perhaps blow it up. Similarly, if you had brought him a shop full of machine tools, he couldn't have powered them and didn't have the high-tensile engineering alloys from which to cut machine parts. But when the knowledge and technology of the Industrial Revolution grew to the point that the two were properly combined, we got the Wright brothers' gasoline-powered shop engine—and flying machines.

So the technology of the Second Atomic Age will be a confluence of two strongly synergistic atomic technologies: nanotech and nuclear. Each brings something the other lacks. A proper combination will have capabilities that are quite remarkable.

Renewable Energy

It's reasonable to expect the supply of energy to continue becoming more available and less scarce, forever.

—Julian Simon

We have already seen how the enormously high energy content of nuclear fuels make nuclear power, in practice, much more like renewables than fossil-fueled power: almost all the cost is in the capital equipment, and the fuel cost comes to a minute percentage of the cost of power.

There are something like 4 billion tons of uranium dissolved in the Earth's oceans. That works out to be over 100 quadrillion watt-years of energy, enough to supply the current American 10 kW level of power to 10 billion people for 10,000 years. Surprisingly, current technology is quite close to being able to extract uranium from seawater economically. The April 20,

2016 issue of the journal Industrial and Engineering Research was dedicated entirely to the subject, for example.

Economical extraction would be a cakewalk with full-fledged nanotech. We could put the entire world back on the Henry Adams Curve and the only environmental impact would be to make the oceans imperceptibly less radioactive. Or maybe not even that.

Uranium is found dissolved in seawater in very tiny amounts, about 3 parts per billion. However, this level represents a homeostatic chemical equilibrium, rather than simply a running sum of the thousands of tons per year of uranium that the rivers have added to the oceans over the Earth's history. The oceans contain 4 billion tons of dissolved uranium at any given time, but ocean floor rocks contain 100 trillion tons, deposited from the water over geological time. If we took out enough to lower the concentration, it would simply start leaching back out of the rocks to maintain the equilibrium.

In other words, if we start taking uranium out of seawater and use it for the entire world's energy economy, indeed a robustly growing energy economy, the concentration in seawater will not decline for literally millions of years.

Plants

If the gigantic new sources of power become available, food will be produced without recourse to sunlight. Vast cellars in which artificial radiation is generated may replace the cornfields or potato-patches of the world. Parks and gardens will cover our pastures and ploughed fields.

The cities and the countryside would become indistinguishable. Every home would have its garden and its glade.

—Winston Churchill, *Thoughts and Adventures* (1932)

If you have a hobby of traveling to wine-producing areas and tasting, you may have noticed a trend: wine grapes are being grown in drier and drier areas, Eastern Washington State and West Texas for example. The reason is that in an area where the natural weather is perfect, on the average, for grape growing, it still varies around that happy medium. If on the other

hand it is usually drier than optimum, you can irrigate up to the right amount quite precisely, and too-wet conditions are rare.

One of the major technological revolutions going on right now spells the nearing end of humanity's first major world-changing technology: agriculture. Currently it looks like this: build a big warehouse-sized building. Inside, it looks something like a Walmart, but with the shelves going all the way up to the ceiling. Everything on each shelf is a growing lettuce, lit by special LEDs on the shelf above. The LEDs emit only the frequencies used by chlorophyll, so they are an apparently whimsical purple. The air is moist, warm, and has a significantly higher fraction of CO₂ than natural air: ideal for growing plants. This is not a greenhouse, however, because it is not dependent on the sun. Supplied with power, it keeps the plants growing 24 hours a day, 365 days a year. The water is recycled, the air is filtered and enriched, and the plants do not need pesticides because pests simply can't get to them. Add all the advantages together and you get something like 300 times as much lettuce per square foot of ground than the pre-industrial mule-and-plow dirt farmer.

All you need is power, to have fresh local strawberries in January in the Yukon or in August in Antarctica.

That is today. The near-term trajectory is pretty obvious: more and different kinds of plants, plants bred or genetically engineered for the environment: stalkless corn, fruit bushes. *Vinifera* (wine grapes) as currently grown are fairly close to this already. Again today, there are substantive efforts to produce lab-grown meat. Early efforts in 2013 produced meat at \$325,000 per pound; a current startup has gotten this down to \$363. Prospects for getting that down to a competitive level are good enough that they are attracting substantial investments from agri-giants such as Tyson Foods. (The current wholesale price of beef is \$3.28 a pound.) Every step toward a true molecular technology will accelerate the trend.

Something like 80% of the land under cultivation in the US produces feed, mostly corn, soybeans, and hay. A much greater chunk of land goes to direct grazing. Right now all of that land serves primarily as a very inefficient solar collector, gathering the energy necessary to drive the rearrangement of atoms from CO₂ back into hamburgers. Second Atomic Age technology not only short-circuits the laborious biological process, but supplies the energy.

By the end of the century, agriculture as it has been practiced for 10,000 years will no longer be necessary.

Many compartments were for the storage of food-supplies, and these were even then being filled by forces under the able direction of the first of Chemistry. “All the comforts of home, even to the labels,” Seaton grinned, as he read “Dole No. 1” upon cans of pineapple which had never been within thousands of light-years of the Hawaiian Islands, and saw quarter after quarter of fresh meat going into the freezer room from a planet upon which no animal other than man had existed for many thousands of years.

—E. E. “Doc” Smith, *Skylark Three*

Your Home Reactor

For 60 years, General Atomic has been making and installing reactors for research that, unlike the big Navy-derived pressurized water reactors used for commercial power generation, are inherently safe—safe enough to be left in the hands of a drunken graduate student. Based on an idea and design of Freeman Dyson, the TRIGA reactors, as they are called, do not rely on external quenching rods or cooling. The uranium-zirconium-hydride fuel is so formulated that it has a negative coefficient of reactivity, which means that the hotter it gets, the less it supports the fission chain reaction. It’s essentially the exact opposite of how an implosion bomb works: squeezing the atoms together, in the bomb, makes a non-critical mass critical; thermal expansion, in the TRIGA, makes a critical mass non-critical. A grand total of about 70 TRIGAs have been operated over the course of 60 years without a significant accident.

The TRIGA stands as a straightforward existence proof that safe reactors can be designed. How small could we make one? In a neutron-reflected, solution-based, moderated reaction, for example, the critical mass of plutonium-241 is 0.246 kg: just over half a pound, or 3/4 of a cubic inch. [\[246\]](#) Cf-251, as noted above, if you have the nuclear technology to produce it, comes in at less than an ounce. Given how dense it is, that’s just one third of a teaspoon. Reactors based on this principle, with the fuel

dissolved in a liquid moderator, have a long history all the way back to Los Alamos, and throughout the Fifties at Oak Ridge. (They are called *aqueous homogeneous* reactors; about 30 of them have been operated worldwide.) The World Nuclear Association tells us:

A theoretical exercise published in 2006 showed that the smallest possible thermal fission reactor would be a spherical aqueous homogenous one powered by a solution of $\text{Am-242m}(\text{NO}_3)_3$ in water. Its mass would be 4.95 kg, with 0.7 kg of Am-242m nuclear fuel, and diameter 19 cm. Power output would be a few kilowatts. Possible applications are space program and portable high-intensity neutron source. The small size would make it easily shielded.

19 cm is seven and a half inches. In a less extreme design, as studied by Steven Wright and Ronald Lipinski at Sandia, you need about 5 gallons of water for the moderation and reflection no matter how little or what kind of fissionable you use, and the reactor core is a sphere less than a cubic foot. The first full-scale reactor, then known as an atomic pile, was built at the Hanford B site to produce plutonium for the Manhattan Project. When it first went into operation, it ran for three hours, began losing power, and stopped entirely after about a day. After a while, it started up again, by itself, and repeated the performance.

What had happened was that unbeknownst to the scientists, fission produces as one of its by-products a certain amount of Xenon-135, which is an extremely effective neutron absorber. Enough ^{135}Xe had built up to take out most of the neutrons propagating the chain reaction.

But Xenon-135 is itself vigorously radioactive, with a half-life of about 9 hours. So if you leave it sitting around for a day or so, most of it is gone, and your reaction can proceed again. Luckily for the Manhattan scientists, the pile had been built twice as big as their calculations called for, so they could essentially use brute force to overcome the Xenon poisoning. With a solid-fueled reactor, that's about all you can do.

But a liquid-core reactor can have the fuel circulating continuously, and have the Xenon-135 filtered out by constantly self-rebuilding molecular sorting machinery, along with any other by-products you may wish to remove. Which means it doesn't have to be overbuilt by a factor of 2. And

that in turn means that if something goes wrong with the recirculating / filtering machinery, the reactor will quench itself.

For the kind of moderated reaction we're looking at, a neutron reflector is used to reduce the size of a critical mass, by roughly a factor of 2. Replace the water jacket reflector with supercritical CO₂ used also as coolant/working fluid for (surprisingly small) turbines. Outside of that, the actual bulk of the reactor would be the shielding of various kinds. The engineering possibilities are endless, and I'm doing nothing but back-of-the-envelope rumination here, but it does seem likely that with nanotech level engineering, the basic physics would allow for a reactor that would fit in a closet and produce on the order of a megawatt. A sanity check is provided by the fact that NASA is currently developing, under the project name kiloPower, a 10 kW reactor of about that size for use in space probes. It is built around a solid U235-molybdenum alloy core "about the size of a roll of paper towels."

Nobody in their right mind would build a reactor like this for power production today (except on a space probe); it would be like buying a million-dollar computer in the 1960s just to play solitaire. But after 50 years of Moore's Law, we do the equivalent all the time and think nothing of it. With the physical productivity of a nanotech industrial base, what would be a ridiculously expensive way of powering a household, or a vehicle, could be perfectly reasonable given the other benefits: put your home anywhere, including a mountaintop in the Canadian Rockies, or on the south Pacific, or indeed surfing the jet stream at 50,000 feet. No power lines, no oil or coal deliveries, no emissions.

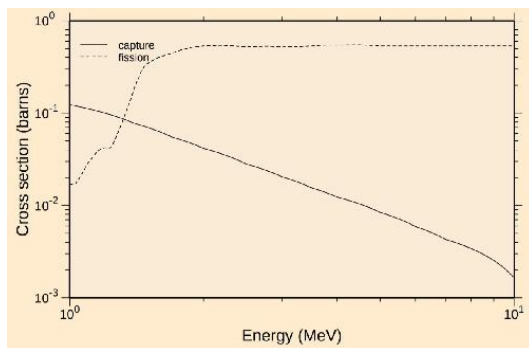
A home reactor providing an average 100 kW, about right for the Henry Adams curve in the Jetson era, would produce about an ounce of fission products per year. Most existing reactors running at that kind of power level don't even bother to remove it from the fuel assemblies.

Chainless reactors

The standard fission reactors use isotopes that can be fissioned by thermal neutrons — ones that have been slowed down to have the same energy as ordinary atoms at room temperature, or about 0.025 electron volts. The

word *fissile* is used for isotopes that are fissionable by thermal neutrons and capable of sustaining a chain reaction. Their cross-section, read likelihood to capture a neutron, is much higher for thermal neutrons than for faster ones such as are produced directly by fission. This is why a moderated chain reaction can use a much smaller quantity of fissionable material than a bomb; the moderation is what slows the neutrons down.

Some isotopes that are not fissile are still technically fissionable; they have to be hit with a much higher energy neutron to fission. Uranium 238, of which 99% of natural uranium consists, is an example. (If U238 encounters a thermal neutron, it tends to capture it, becoming U239 and beginning the process that turns it into Plutonium.)



High-energy neutron cross-sections for U-238: below 1 MeV capture is much more likely, but above it fission dominates. (LANL)

So if you have a source of high-energy neutrons and a chunk of U-238, you can build a reactor that doesn't use a chain reaction, and in fact can't run at all if the external neutrons are not supplied. It would be runaway-proof, meltdown-proof, and could use natural unenriched uranium (or the more abundant thorium) so no enrichment facilities (such as might be used to produce bomb-grade material) are necessary. That makes it both safer and cheaper than current reactors.

Where do you get the neutrons? One option is a particle accelerator. You can't accelerate neutrons directly, but you can throw charged particles, like protons, at materials which will give off neutrons when struck, in what is called spallation. Of course you have to use some energy to run the accelerator, so it works out to a question of efficiency. There appears to be

at least one government-sponsored project to attempt this, so we can assume the engineering projections are at least halfway favorable. The other way to get high-energy neutrons is by fusion, notably of deuterium and tritium. This reaction produces helium and a 14 MeV neutron. If you can't get breakeven from the fusion alone, you can pick up in the range of 200 MeV from the fission.

Safety

In 2006, MI6 agent (and former Soviet spy) Alexander Litvenenko was assassinated by the expedient of slipping 26.5 micrograms of Polonium-210 into his tea. Polonium-210 is a vigorous alpha-emitter; if introduced into the body efficiently, i.e. by direct injection, one microgram is a fatal dose, causing death by radiation sickness.

How can we in good conscience recommend a world energy economy based on nuclear power if nuclear materials are so deadly in such microscopic quantities? It might help to re-describe the incident:

Litvenenko was killed by Russian agents who slipped *ten million dollars worth* of Polonium-210 into his tea. Even so it took him three weeks to die. Once MI6 figured out what had happened, the source of the attack was easily traced because there is only one facility in the world that produces it, a Soviet-era plant named Avangard in the city of Sarov. They gave it to him using a method that would have worked with just about any poison. If instead they had given him the metal as a scrap of foil in an ordinary paper envelope, he could have handled it in perfect safety.

Polonium-210 is an unusually dangerous isotope [\[247\]](#) and then only in unusual circumstances: if administered internally. It is rare—so rare the Russians thought it wouldn't be identified—and expensive to manufacture. It is not part of the power cycle.

Botulinum toxin is about 5 times as deadly by weight as Polonium-210. Far from being extremely rare and difficult to manufacture, it is sometimes made accidentally when amateur canners don't pasteurize their jams and jellies properly; the anaerobic bacteria responsible are everywhere. It is widely produced and even more widely handled ... as a beauty treatment ("botox").

The point is straightforward. The specific toxicity of a substance tells you nothing whatsoever about whether it is any kind of a public hazard. That depends on many factors, but one of the main ones is how much of the stuff it is necessary to handle for the purpose it is used for. We may have an intuition that a microgram of something must necessarily be easy to misplace, but when we realize that we are talking about something that is at once very expensive and very powerful, we can begin to see that people will invest an amount of care and precaution based on those properties and not its physical size. As an example, tritium can be dangerous because it chemically substitutes for hydrogen and could incorporate into water to be absorbed into bodies. But tritium costs \$30,000 per gram; you don't just let it escape!

This is where the factor of a million in energy content makes so much difference. Suppose for example you use 1000 gallons of gas per year in your automobile. That comes to 60,000 pounds of gasoline you have to handle and pump over the 10-year life of your car. During that time, the National Fire Protection Association tells us, there will be about 50,000 fires and explosions at American gas stations. There is the same amount of energy in half an ounce of thorium (for example). If we but understood how to use it at that scale, you would never fuel your car at all; fuel for the car's lifetime would come built in, factory sealed.

At the same time, the flip side of the equation is that nanotech makes it much easier to clean up any accident or cure any actual exposure. We will be building cell repair machines to prevent and cure cancer anyway; we will be building artificial organs because they work better than the organic ones. In the Second Atomic Age, Litvenenko would have gotten a text from his left kidney telling him that it had collected 26.5 micrograms of Polonium-210, and what would he like to do with it?

Jetpacks



Without too much notice or fanfare, it turns out that one of the “where is it?” technologies of sci-fi, this time more Hollywood serials than serious novels, have arrived. There are now two companies making real working jetpacks: Martin Jetpack in New Zealand, whose flying machine sports a custom Wankel engine and a couple of ducted fans, and Jetpack Aviation in California, whose backpack-sized offering uses actual gas turbines. These differ from the gimmick rocket packs of the 60s (and James Bond movies) which were hydrogen peroxide rockets and could only carry fuel for 15 or so seconds of flight; the new air-breathing ones change seconds to minutes. Even so, the jetpack is inherently low-efficiency because of the small thruster area, and at the same time highly sensitive to fuel weight. This is obviously the kind of application where nuclear power densities, if we can achieve them in such a small package, would make a huge difference, stretching the minutes-long flight times of the current machines to hours. And that would change them from cool toys to useful (if noisy) flying machines.

Nano DementiCar

Let us not forget that significant improvements in technology will be possible with nanotech, compared with the technology we have today. By far the most important aspect is that the productivity of nanotech allows the average person to afford things that would be outrageously expensive if made with today's bulk technology. Even if all you consider is a flying car we could build today, but at great expense, nanotech makes the difference, just as Henry Ford's assembly line did a century ago. But nanotech also enables significant improvements in the machine itself, including improvements in basic capabilities but also self-maintenance and repair. Your flying car today could have been turbine powered, but it would still have run on fossil fuels. That means you would have a tradeoff between VTOL and range or load. With nanotech, even if we are still thinking in terms of oxidized chemical fuels, that largely disappears. Full atomic control means that we do not have to thermalize chemical potential energy to use it. This in turn means that you don't have to strain the bounds of material science to accomodate ultra-hot temperatures in your engine. It also means you get three or four times the usable energy from a given quantity of fuel, instead of sacrificing it on the altar of thermodynamics. Hydrogen has three times the energy to weight ratio of gasoline; use it in a fuel cell to produce electricity directly, or in a nanotech power mill with the same function, and you get a further factor or three or so. The Cirrus family-sized jet carries 2000 pounds, a full ton, of jet fuel; this would be cut down to say 200 pounds in hydrogen for a similar 1000-mile range. The bleeding edge of current practice is fuel cells with the power-to-weight of piston engines, and hydrogen storage that is heavier than the same energy in gasoline. You could do a usable convertible with that, but the other drawback is cost, which is still quite high. Nanotech could very reasonably be expected to ameliorate all three of these factors, producing an affordable VTOL car.

It's probably worth mentioning that with nanotech, producing the hydrogen from virtually any energy source at all is trivial, and compressing, cooling, and storing it is considerably easier than with current-day techniques. Even

so, storing energy as hydrogen, while considerably lighter than carbon-based fuels, will very likely be just as bulky. But of course for flying machines, it's the weight that matters.

The next big advantage for the nanotech aircraft is the weight of engines, including the fuel-burning power mills as well as the electric motors that will push the air. As we pointed out in Chapter 4, these are so small as to be entirely negligible. Structural weights can also be smaller, although current materials practice is farther along toward the achievable limits than engines are. Still, putting the two together, you get a significant ability to make powered, morphing structures where today you would have only a rigid one. This would include both wings and propellers; extensible propellers or even extensible ducted fans would be possible.

You will not see propellers or ducted fans, however; the principle of many, smaller, impeller devices in arrays that are robust to any individual failure, which are more quickly responsive to control inputs, and can tailor the airflow in detail will very likely dominate designs. Given the light weight likely possible in power supplies, they might make use of ionic thrust. Alternatively they might have millions of tiny blades interacting with the air in regimes small enough that sound and turbulence are avoided. Or both. This means a compact vehicle that is VTOL but takes off with the whoosh of a strong wind through the trees instead of an earsplitting roar. The trick, for the designer, is to keep the entire downstream jet subsonic and as close to laminar as possible.

A note to readers of *Nanofuture*: in that book I proposed fancloth, which would be an extreme case of the many small thrusters idea, and which produced the romantic image of the aircar looking like a sailboat as it sailed quietly off into the sky. As a practicing pilot, I am now more aware of the issue of gusty crosswinds, which would tend to limit the use of sail-like structures, and the value in general of high wing loading. But as we have seen, the planform of an ordinary car is a perfectly usable thruster area, and would be conducive to a somewhat more robust all-weather vehicle.

Power

Although hydrogen (or, for that matter, Jet-A) is a usable fuel for a flying car, we would like to use tritium, as in a Betacel. Of all the beta emitters,

tritium at the same time produces low-energy and thus relatively easy to handle particles, but still has 10,000 times the energy per weight of gasoline. If you want it easy to handle, give up a factor of five by making water with it; after all tritium is still chemically hydrogen. Your 1000-mile fuel tank is now about a pint of T_2O (or liquid NT_3) instead of a ton of oil. That is, if you can figure out how to extract the energy. Like any radioisotope, the energy in tritium is delivered regularly on an exponentially declining schedule; you get the first half over the course of 12.3 years. If you were depending on the natural decay rate of tritium for your power, you would have to carry enough that you might as well use chemical fuel. It is easy to stimulate emission of some kinds of decay in quantum mechanical systems: that is what happens in a laser. Unfortunately for tritium (or any beta emitter) the electron is a fermion, and laser-style stimulation only works with bosons. There is one situation where electrons can act to some extent as bosons, namely as Cooper pairs in a superconductor. This is only achieved at extreme (low) temperatures in unusual molecular structures, and phonons are involved, but it does happen. Could we make something like that work to stimulate beta decay? Short answer: I don't know. We do know that beta decay rates can be affected by the electronic environment—neutral ^{187}Re atoms have a beta-decay halflife of 42 billion years, while the fully-ionized nuclei have a halflife of 33 years. [\[248\]](#) Electromagnetic fields at or past the Schwinger limit are also known to affect decay rates as well, but this is an intensity that also produces electron-positron pairs from the vacuum—it could easily cost more energy than you get back! We don't precisely know the half-life of an unbound neutron, one outside an atomic nucleus. The two main ways we have of measuring it give results of 877 and 887 seconds, respectively. The obvious first guess is that there is some difference in the methods *that we don't understand* that is affecting the decay rate. I can say with some confidence, however, that if it does turn out to be possible to stimulate decay, we will need nanotech to do it on a small enough scale to be useful. There many isotopes that contain huge reserves of energy, and other ways of poking them short of a neutron-mediated chain reaction. Coherent phonons might even work. I would be fairly surprised if

by the end of the century, we hadn't found materials and techniques that made chemical fuels look quite wimpy by comparison.

Fusion

Cold

Since 2004, the major advance in the field scientifically has been the discovery, with apparent multiple replications, that the effect can be enhanced by the use of a complex (high-voltage, multi-frequency) stimulating signal instead of the DC current of the earlier experiments. The evidence for some physical effect had mounted to the point that CBS's *60 Minutes* produced an episode in 2009 saying "Cold Fusion is Hot Again." [249] Far be it from me to cite a *60 Minutes* episode as evidence of anything, but in the process of doing research for it, they enlisted Robert Duncan, vice-chancellor for research at the University of Missouri (which, by the way, operates the nation's largest university research nuclear reactor). Duncan was initially skeptical of cold fusion claims, but upon investigation became convinced that excess heat was being produced and was ultimately instrumental in founding a cold-fusion research institute at U of M.

Also in 2009, the Defense Intelligence Agency produced a technology forecast report [250] entitled *Worldwide Research on Low-Energy Nuclear Reactions Increasing and Gaining Acceptance*. Its title sums up its contents pretty well. It concludes, "For years, scientists were intrigued by the possibility of producing large amounts of clean energy through LENR, and now this research has begun to be accepted in the scientific community as reproducible and legitimate." That is over-optimistic, but there has developed a separate subculture of LENR researchers and entrepreneurs with their own conference and publications, and a body of knowledge and techniques which has apparently improved to the point that the key experiments are now much more reproducible than they were 25 years ago. Currently, the Japanese government is funding LENR research through its NEDO (New Energy Development Organization) agency.

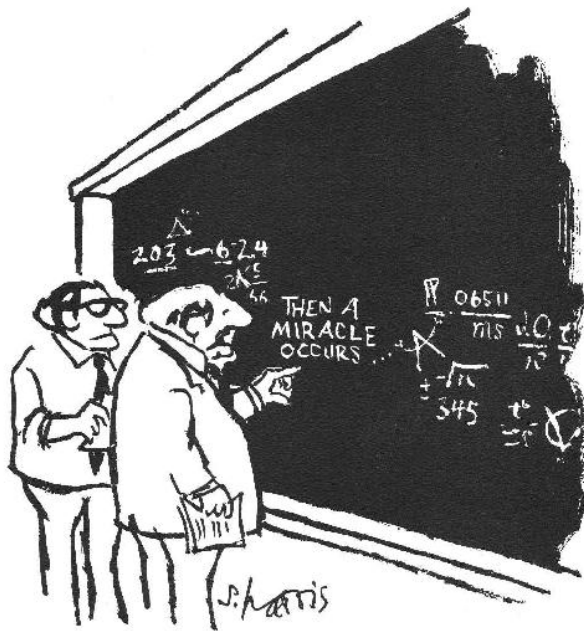
Miracles

It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.

—Sir Arthur Conan Doyle, *The Adventures of Sherlock Holmes*

The main business of Natural Philosophy is to argue from Phænomena without feigning Hypotheses and to deduce Causes from Effects.

—Sir Isaac Newton, *The Opticks*



"I THINK YOU SHOULD BE MORE
EXPLICIT HERE IN STEP TWO."

(© Sidney Harris, *ScienceCartoonsPlus.com*. Used with permission.)

Like most people in the scientific world, by the end of 1989 I had accepted what was the general consensus, that cold fusion had been a big mistake, based on bad laboratory technique, and there was nothing to it. It was only fairly recently, after having been personally introduced to the Machiavelli Effect in connection with nanotechnology, that I thought to reconsider. Upon investigation, it turned out that the experimental side of cold fusion has made a reasonable amount of progress in the past quarter-century. I

attended the 25th anniversary conference on cold fusion at MIT, and found stable, sane people, with respectable scientific credentials, and decades of careful experimental work. Addressing a local science interest group on the subject, I even discovered that an acquaintance of mine had been an eye-witness to the original Fleischman and Pons meltdown at Utah.

The major problem is that the state of theory is still more or less that of the famous Sidney Harris cartoon: “And then a miracle occurs.” The cartoon had been around for a decade by the time the cold fusion flap happened in 1989, and very likely contributed to the choice of phrasing in John Huizenga’s book [\[251\]](#) in an attempt to discredit it.

Huizenga’s physics-based criticism, unlike some of the other material in his book, remains a fair guideline to the problems a physics theory of cold fusion must overcome. There are three “miracles” that have to be explained:

1. The Coulomb barrier: the amount of energy necessary to force two nuclei close enough to fuse is much higher, by orders of magnitude, than the amount of energy any electrochemical process can provide one atom.
2. The reaction pathways: when deuterium nuclei do fuse, they almost always produce tritium and a proton, or helium-3 and a neutron, which are not detected in appropriate quantities in cold fusion experiments.
3. The output: even if somehow you managed to get the deuterium to fuse and stay fused in the form of helium, that pathway produces very energetic gamma rays (which are also not detected), not heat spread out evenly over tens of billions of atoms.

One single D-D fusion event, if resulting in helium, produces 24 MeV of energy, enough to raise a typical bacterium one degree Celsius. The bacterium is big enough to contain 33 billion or so heavy water molecules. If you fused the pair of deuterium atoms in each molecule, you should get a temperature of 33 billion degrees, if that made any physical sense, which it doesn’t. Instead, when we do force deuterons to fuse in particle accelerators, all that energy is concentrated in the one helium nucleus that wants to form, and almost always blows it to smithereens.

To date, most of the theorizing about cold fusion has gone into trying to understand the first miracle, getting fusion to happen in the first place. To

be fair, all of the effort in hot fusion has gone into the same phase of the problem, and has as yet failed to solve it.

Neutrons

It was of course neutrons that make the fission chain reaction possible. Lord Rutherford, the discoverer of the nucleus and one of the pre-eminent physicists of the early 20th century, thought self-sustaining nuclear reactions “moonshine” because of the Coulomb barrier; but that was before the discovery of the neutron. Neutrons are not repelled from a target nucleus, and thus don’t need high energy and lots of luck to hit one (remember, only one in 20,000 alpha particles hit a nucleus squarely head-on to bounce back). But where is the neutron supposed to come from? One possible source is a process called electron capture, in which an electron and a proton combine to form a neutron. The main problem with this is that when you put a proton and an electron together, what you actually get is a hydrogen atom. The electron, by the basic principles of quantum mechanics, wants to be big and fluffy; it takes a lot of energy to squeeze it down to the size of a neutron. It’s like trying to putt a beach ball into the hole on the ninth green. In fact, it takes more energy to squeeze the electron down than it would to overcome the Coulomb barrier between deuterons directly. But that much energy is easily available in a macroscopic electrochemical experiment; the problem is concentrating it onto just one electron. Even Einstein speculated that some such process might occur, in recently-discovered correspondence. In latter days, Allan Widom, professor of physics at Northeastern, has published theories of cold fusion involving electron capture. [\[252\]](#)

Unfortunately, electron-capture based theories of cold fusion have a weakness: the other two “miracles.” Every time a neutron falls into a nucleus, enough energy is released to produce a gamma ray in the low MeV range; these are not observed (at least, in the quantity that the heat generation would appear to require). Furthermore, the neutrons themselves are not detected either. And once the neutrons start some nuclear process, there’s no mechanism to explain how all the energy released turns into heat and only heat.

To be fair, there are phenomena, notably elemental transmutation, associated with cold fusion in some experiments that are very hard to explain without free neutrons being produced. But we would like a theory in which whenever some mechanism causes miracle 1 to happen, it *almost always* also causes miracles 2 and 3. By far the most believable possibility for that is simply that they are all the same mechanism. In the Widom-Larsen theory, for example, the same “heavy” electrons that are capable of being captured are able to absorb outgoing gammas. There does remain the problem of the ultra-cold delocalized neutrons that are supposed to form (so they can’t escape and be detected), which seems just a little bit *ad hoc*.

Phonons

I think I can safely say that nobody understands quantum mechanics.

—Richard Feynman

Hagelstein champions a theory that appears to bag all the miracles with one phenomenon: quantum coherence. It is based on the idea that there is a direct quantum-mechanical coupling between some nuclear transitions and phonons in the solid state.



Two leading cold fusion theorists: Peter Hagelstein (left) and Allan Widom. (Photo by the author)

A phonon is a quantum of heat, in just the same way that a photon is a quantum of light. It bears the same relationship to the physical motions of the atoms in a substance that the photon does to the wave motion of the electric and magnetic fields that make up the classical description of light.

In the classical description, a light wave is a coordinated oscillation of the electric and magnetic fields, and it exerts a force directly on the electrons of an atom in accordance with Maxwell's equations. A little wave jiggles them a little, a big one jiggles them a lot. In theory. But a century ago, physicists realized that's not what actually happened. Whether an electron got thrown out of an atom, for example, depends not on the amplitude of a lightwave, but its frequency. Not its brightness, but its color!

It was in fact Einstein who won the Nobel prize for seeing the theoretical implications of this "photoelectric effect," and he famously grappled with an intuitive understanding of it ("God does not play dice") for the rest of his life. So has everyone else. Even Schrödinger is quoted as saying, "Anyone who is not deeply disturbed by quantum mechanics has not understood it." But the bottom line is that they developed a theory which, while intuitively frustrating, predicts the result of experiments very precisely, explains the structure of atoms in a way classical physics simply could not, and has allowed us to design a host of devices, such as transistors, LEDs, and lasers, that rely entirely upon quantum effects for their operation.

For example, one of the wierd quantum mechanical phenomena that makes a laser work is coherence. If you "pump" the atoms of a material to a higher energy state (itself a quantum concept), normally they will just drop back down at random times, emitting photons in random directions. But it is possible to arrange things so that the atoms are stimulated into a coherent state change, emitting all the photons at the same time, in the same direction, with the same polarization and frequency. And it happens much faster than a non-coherent process would have done.

So if there were a coherent quantum-mechanical coupling between nuclear degrees of freedom and phonons in the atomic lattice of the palladium, it would provide at the same time (a) a channel for excitation in the metal to overcome a nuclear energy barrier, (b) affect the reaction pathway by providing a wide-open "drain" for the energy along one of them, and (c) a way for the energy to reappear as heat instead of hard radiation.

In addition to this intuitively appealing explanatory stance (and in spite of an intensely formidable mathematical exposition in his papers), Hagelstein's theory is attractive because it has apparently predicted some otherwise unexpected results in experiments. In one, for example, optical stimulation of an F&P type cell enhanced the excess heat effect at a

frequency associated with the passage of deuterium through the palladium lattice, but not at other frequencies. However, it's early days yet. It seems at first blush that saying there might be a quantum coupling between phonons and some nuclear degree of freedom is indistinguishable from magic. But if you look closely, it's not completely insane. The phonons of interest are in the terahertz frequency range, and are composed of vibrations of the atoms and in particular, because that's where all the mass is, of the nuclei. But when you push an atom, what pushes the nucleus is the electromagnetic field of its electron cloud. Inside the nucleus, this pushes on the protons but not the neutrons, [\[253\]](#) so we can assume that there is at the very least some dependence on intranuclear forces to move them all together. It turns out that the term in the Dirac equation that allows it is relativistic, and is little used in calculations about solids that are standing still. We know that there are some very counter-intuitive things associated with relativity.

Getting to Work

Let us suppose, for the sake of argument, that Fleischman and Pons were right. Or more precisely, right about a heat effect, though wrong about the fusion pathway. This does not necessarily mean that the energy millenium is right around the corner. To begin with, palladium is rare enough—it's a platinum-group metal that is used in jewelry; indeed my wedding ring is palladium!—that generating capacity would be fairly expensive even if the F-P cells had worked first time, every time. The most reliably reproducible LENR experiments I know of, Mitchell Swartz's "nanor" pre-loaded nano-material composite wires, produce 100 milliwatts of heat from 1 milliwatt of electricity. He told me they cost over \$100,000 to make. This should be a scientific bombshell; it is a commercial dud.

There is one cold fusion effort which, for whatever reason, largely avoided the Machiavelli Effect that happened to the larger community. Operating out of the Navy labs at SPAWAR, they had a somewhat novel approach to the electrolysis, not only loading deuterium into their electrodes but co-depositing more palladium at the same time. Then instead of doing calorimetry to look for excess heat, they looked for radiation using standard

methods. They found it, in unambiguous form. As a result, they have 50 peer-reviewed publications in 12 different scientific journals, and 2 patents, [\[254\]](#) which are extremely hard to come by for cold fusion researchers. Their cells specifically produced high-energy neutrons such as might be used to run a chainless reactor burning U-238. This has been noted in the appropriate places and there is apparently a project afoot to develop such a reactor for use in spacecraft.

Although there are at present several companies with apparently promising developmental results attempting to commercialize various forms of LENR reactors, there has been a steady stream of such attempts since 1989, and nothing useful has come of any of them. There is a huge difference between demonstrating an effect exists in the lab, and making it reliable, powerful, and above all inexpensive enough to be economically viable in the real world. It may be that someone has made enough of a breakthrough in engineering to produce a commercially viable design, but I wouldn't recommend holding your head underwater while you wait for it.

On the other hand, I wouldn't be enormously surprised if someone does manage it sometime in the next decade or two. The key would be a device that was (a) reliable, and (b) had a power level *and* power gain large enough to run a heat engine to supply the electricity to run itself. The first commercial versions wouldn't have to be world-beaters; they would just have to *work*, enough to attract a lot of commercial interest and thus money. The market is good at incremental improvements.

The really revolutionary development, however, would be when we got enough experience to gain a solid theoretical understanding of what's going on in atomic-level detail, *and the technology to manipulate the conditions at will*. If you took a detailed blueprint of a jet engine back to Leonardo da Vinci in a time machine, he could have done nothing with it. There are more things in the microscopic structure of the solid state, Horatio, than are dreamt of in your philosophy. If there really is a back door in obscure quantum mechanics between nuclear degrees of freedom and the solid state, it seems quite likely that the configurations of atoms that unlock it are produced rarely and at random by bulk manufacturing methods. With nanotech we could (a) analyze what was going on at the atomic scale in detail, and (b) reproduce it reliably.

The mind-boggling, Failure-of-the-Imagination implications of a new physics backdoor are not so much that we might be able reliably to reproduce a couple of decades worth of laboratory curiosities. They are that a solid understanding of what is going on could give us a powerful handle to control, at the single-atom scale, all the different forms of nuclear energy we already know about. And that could give us Tom Swift's (and Isaac Asimov's) "atomic batteries." You could afford to surround each uranium atom with 20 million atoms of carbon-based nanomachinery to suppress, stimulate, direct, and tap its nuclear reactions, and still have something with the energy density of gasoline.

In current technology, we have no way to fuse two nitrogen nuclei to produce silicon. But if you could, it would produce just about exactly one million times as much energy per weight as gasoline. Fusing the approximately one gram of nitrogen in one liter of air, a good hard sigh, would produce a quarter teaspoon of sand as ash, and enough energy to run George Jetson's 1341-horsepower flying car ... for 13 hours. A one-liter flask of liquid nitrogen would take it 6 million miles, and would last the average 1-hour per day driver 35 years.

The real tragedy of the cold fusion episode is not about fusion, or quantum mechanics, or indeed energy *per se*. It is that over the course of the Great Stagnation, the funding-bureaucracy / academia complex has lost the ability to do purely experimental, observation-driven research. Failure of Imagination is now the law of the land.

The US spends roughly a trillion dollars a year on energy. We spend approximately another trillion on conservation, green mandates, climate change studies, biofuels, solar and wind subsidies, and \$100,000 battery-powered cars. In other words, something like \$2T, more than 10% of the whole economy, could be replaced if we found a clean, cheap, small, distributed energy source—and that's not even counting the Jevons Paradox effect. The Department of Energy review a decade ago found about half a chance that a cold fusion heat effect was real. Even if we stipulate that there might be only a 1% chance that the effect is real and could be turned into something useful, you would have an expected value of \$20 billion a year. A \$1 billion a year investment in LENR research might pay off handsomely. In fact, that's about how much is spent on hot fusion research.

For comparison, we spend around \$4 billion per year on dog grooming.

Hot



It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter, will know of great periodic regional famines in the world only as matters of history, will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speeds, and will experience a lifespan far longer than ours as disease yields and man comes to understand what causes him to age.

—Lewis Strauss, AEC Commissioner (1954)

Lewis Strauss' famous "too cheap to meter" comment was made about the prospect of power not from fission but from fusion. With people like commissioners of the AEC telling them that fusion was right around the corner, the science fiction writers of the 50s can to some extent be forgiven for over-expecting it. We did after all actually produce fusion in hydrogen bombs, and fusion happens in the sun, converting simple, plain ordinary hydrogen into completely innocuous helium. This sounds like a dream power source. Yet though we've spent roughly a billion dollars a year in the meantime on the search for fusion, it remains stubbornly the power source of the future. (The schedule for first plasma in Europe's enormous ITER experimental fusion reactor has been pushed back to 2025, and adding tritium to the fuel mixture to 2035.) If there was one really major failure in forecasting among technologically literate SF writers (e.g. Clarke expected it in 1990), fusion would be it.

To understand why, we must start with our apparent example in nature: the Sun. Fusion only occurs in the solar core, about one percent of the volume of the total, where conditions are really, really extreme. The temperature is 15 million Celsius; the pressure is 265 billion atmospheres; and the hydrogen plasma is compressed so much that one gallon of it weighs 1200 pounds. (Under Earthly conditions, 1200 pounds of hydrogen would fill a balloon big enough to lift 7 tons.) Under these ridiculously extreme conditions, hydrogen will fuse into helium in a three-step process. The first step, in which two protons (hydrogen nuclei) fuse and emit a positron to form a deuterium nucleus, takes an average of a billion years to happen to any given proton. (The second step takes 4 seconds, and the third takes 400 years.) This is not a fast reaction, and that's a good thing. If the Sun burned its hydrogen as fast as a hydrogen bomb, it would all have been gone billions of years ago! The Sun is a barely-burning bed of coals well banked against the long interstellar night. But the bottom line is that a volume of solar core equal to the displacement of your Subaru's engine (and weighing 660 pounds) only produces half a watt of power.

The reason we are able to achieve fusion at all, in an H-bomb, is first and foremost that it isn't plain hydrogen being burned—it's deuterium, tritium, and lithium, already one or more steps along the reaction sequence in the Sun, and in particular past the billion-year step. The other major difference is that the fission bomb used to ignite the thermonuclear reaction isn't at 15 million degrees; it's at 400 million degrees, so hot it's not white-hot, or even UV-hot, but X-ray hot.

Shrouded in the mists both of history and of secrecy is the fact that even then it's quite difficult to make the fusion go. The Los Alamos scientists produced two completely different kinds of fission bomb in just a couple of years as part of the Manhattan Project, starting from scratch; both designs worked on the first attempt. They worked for another 5 years after the war basically to prove that all their best attempts at a fusion design wouldn't work. It wasn't until 1951 that Stanislaw Ulam had the key insight that led to the ingenious design that ultimately did.

In simplest terms, there are actually four explosions. First (1) is the chemical high explosive that compresses the plutonium core, which causes the fission explosion (2) of that core. This is designed to produce most of its energy in the form of X-rays, which are directed to heat up a sleeve of

plastic (e.g. polyethylene and/or polystyrene). The amount of energy deposited this way causes the sleeve to explode (3) with a violence far greater than could be achieved by a chemical explosive, and it is that explosion which compresses and heats the fusion fuel (4) inside the sleeve. Even the first-stage chemical explosion, tiny in power compared to the nuclear ones, would destroy the device. One of the major feats of design in the bomb is the way the falling-domino sequence of successive explosions happens in the short microseconds while the bomb is in the process of converting itself into incandescent plasma. There is no hint of a chance that a reactor using anything even vaguely like this process could survive even a millisecond of its own operation. Some of the smartest physicists in the world have worked for 60 years to produce the necessary conditions in a machine that doesn't use an atom bomb as a fireplace match.

So far the best attempts, such as the Sandia Labs Z-machine, are trying to do the same thing with super-fast electrical discharges from a warehouse full of capacitors into a capsule the size of a spool of thread. Of course the capsule is vaporized, but the explosion can be contained in a chamber the size of a house. Experimenters are in the process of adding tritium to the fuel mixture (a non-trivial operation, especially given the radiophobic regulations the national labs impose on themselves) and hope to get to energy breakeven in a few years. Time will tell.

As of even date, the only way to produce net energy from fusion with existing technology is essentially the same idea, but using actual thermonuclear bombs and a chamber thousands of feet across, probably underground. The chamber would be filled with steam which the bombs would heat up, and the heat would be drawn off to run turbines of conventional design. Two explosions a day would produce as much continuous power as a standard nuclear plant. This was seriously studied in the 1970s under the aegis of Project Pacer; although challenging, there were no technological showstoppers. However, the requirement of producing a steady supply of hydrogen bombs was a major liability, and the economics were not as good as conventional fission reactors.

Aneutronic

Even if we do manage to produce fusion of the kind of fuels used in H-bombs in a magnetic or inertial confinement machine, it remains a process that produces copious radiation and neutrons. Although the ignition temperatures are higher, it remains a holy grail to do a form of fusion that produces most of its energy in the form of alpha particles, which being charged can be converted directly into voltage by various electromagnetic or electrostatic mechanisms.

There are several projects attempting to do this today in various styles of machines. The most common of the attempted reactions is the proton-Boron-11 fusion/fission one, in which the proton, i.e. hydrogen nucleus, fuses with the boron to produce a highly excited state of Carbon-12 which promptly breaks up into three alphas (helium nuclei). The most propitious energy for the proton to have is 675 keV; the energy carried away by the alphas is 8.7MeV, or roughly 13 times the energy you started with.

Tri-Alpha Energy in California, funded by Paul Allen among others, and LPP Fusion in Lawrenceville, NJ, for example, have been attempting the reaction with plasmas confined in magnetic fields. It can be difficult to judge progress from outside, but Tri-Alpha is generally well thought of, and the most cogent critique of LPP I can find boils down to “yeah, we know all about that, other people are trying it and have done for years.” More power to all of them.

Another way to get kilotesla fields is with a petawatt/picosecond laser pulse. A recent simulation study at New South Wales [\[255\]](#) has a laser trap and ignition pulse touching off a 14 milligram sample of H-B11 and capturing 1 GJ of pure electricity, no boilers, turbines, or generators necessary, at an energy density of 71.5 TJ/kg. These approaches are room-sized machines costing millions, instead of the skyscraper-sized machines costing billions of the ITER variety. Some of them could produce a car-sized power unit given a nanotech technology base. I would not be terribly surprised to see some results in H-B11 fusion in the coming decade.

——Bottom Line——

In current-day futurism, it has become common to suppose that information technology is the wave of the future, and to view the big, fast, and powerful visions of the future from the 50s and 60s as quaint. This is not a view based on any deep understanding of the possibilities of physical technology. The boundary of the technium is poised to pass beyond the informational halo of the Second Atomic Age into the almost indescribable physical capabilities of the complete control of the structure of matter.

An amusing side-prediction of the fusion energy story is that for a few decades at least, a fusion energy machine is likely to be fairly bulky, the same way fossil fuel engines were early in their history. Your flying car may wind up looking like a 1959 Cadillac after all.

We could have by 2062 not only flying cars, but flying homes. Farming could go the way of hunting, from a necessity to a pastime, as food production moves to factories and then to your “Foodarackacycle” countertop synthesizer. We will have the ability to remake the entire Earth’s climate and topography however we like.

Technologically, the future for flying cars is quite bright. We could build very serviceable ones now; the Second Atomic Age makes them easy and cheap. On the flip side of the equation, the end of agriculture means that vast amounts of land will become available for far-flung homes if only fast transportation is available. Thus we may have both a supply-side push and a demand-side pull over the course of the rest of the century.

Add to that the fact that our current social decision-making systems are completely incompetent to make the kind of investments in transportation infrastructure that would approach optimal use of the newly available land. In the WWII era, Heinlein could imagine a centralized, mechanized, continental-scale system with expert national management in *The Roads Must Roll*, but in today’s world a system with more private (sophisticated semirobotic flying cars) and less public (no need to build roads in the sky) components seems considerably more likely to work.

The Second Atomic Age could very easily be the age of flying cars, if only we have sense enough to do it.

22 Robots

Mike looked around him while the roboticist went on. The men were looking pretty bored. They'd come to get a briefing on the reason for the trip, and all they were getting was a lecture on robotics.

—Randall Garrett, *Unwise Child*

Do Not Pass GO

The jets of the hundred for the idea of the Miny-pour from a seemed planet, now on when the left the band should blow that to have him from glarge. But they were always for the grim, though even for the very arm-visions.

—half-trained LSTM MRNN

"Dejah Thoris," he said. "I'll be somewhere, which may be the meaning of all the cabin. But I know that you've got some of his heart all your teleceiver of the Lensman."

—two days later

A decade ago in *Beyond AI*, I took up cudgels against those who were predicting a major takeoff in artificial intelligence by virtue of a self-improving super-AI. Long before that happens, I said, we will see something a bit more mundane but perfectly effective: AI will start to work, and people will realize it, and lots of money, talent, and resources will pour into the field. "... it might affect AI like the Wright brothers' Paris demonstrations of their flying machine did a century ago. After ignoring their successful first flight for years, the scientific community finally acknowledged it; and aviation went from a screwball hobby to the rage of the age, and kept that cachet for decades. In particular, the amount of development effort took off enormously." That will produce an acceleration of results, which will attract more money, and there's your feedback loop. The amount of money going into aviation before 1910 was essentially nil (Langley's grants to the contrary notwithstanding). Once people caught on that airplanes really worked, though, there was a sensation and a boom. By the end of the 1920s, Pan American was flying scheduled international flights in the 8-passenger Ford Tri-motor. The ensuing exponential growth in capabilities, continuing unabated right up to the Sixties, was very much part of the zeitgeist of the "future we were promised."

Something of the kind appears to be happening in AI now. In just the past few years, a breakthrough from an unexpected source, deep learning in multi-level neural networks, has brought significant new capabilities. In some sense, “deep learning” is just a buzzword phrase, since the techniques are basically just the same back-propagation of error terms that has been used since the 1980s. But like the advances in self-driving cars, progress on a lot of small improvements and optimizations combined with substantial new processing power in the form of GPUs, and the availability of large datasets for training, have left us with the ability to train a neural net in an hour on a dataset that took weeks in the 90s. That lets us train networks with 22 levels where the standard a couple of decades ago was 2 or 3. These of course are combined with (and enabled by) the expected progress in various other parts of the field ranging from processing power to robotics. A decade ago, we did not have robots who could learn manual tasks by watching them being done and practicing them; now we do. [\[256\]](#) A decade ago, you were better off fat-fingering your text message into your smartphone and suffering the indignities of auto-correct, than trying to use the speech recognition. In my recent experience, that has changed, and recognition works better than “typing” on the phone’s tiny screen keyboard. As an experiment to see what the state of the art is like, I took a popular open-source collection of learning tools [\[257\]](#) and trained a multi-level recurrent neural net on a 50-megabyte corpus of adventure and SF novels. Untrained, the model produces complete random-character gibberish. After one night’s training on my not-particularly-powerful workstation, it was capable of producing the sample you see above. It starts with no knowledge whatsoever, even implicit, of the structure of language. By the time I took that sample, it had picked up the idea of words, accumulated a good vocabulary, understood enough of sentences to capitalize and punctuate, and enough grammar and parts of speech to produce coherent prepositional phrases. It fell a bit short of full subject-predicate sentences after one night, but a couple of days later was getting close. When it did decide to make up a word, it produced something reasonable, pronounceable, even creative. (And it lends a certain credence to the author’s standard complaint that ideation recapitulates inebriation!) The reason this is amazing is that the task the model was set to learn was simply to predict the next character given a sliding 50-character window in the text. It worked out all of the concepts

and structure completely from scratch. This is an extremely powerful capability. It may very well take a full decade or two to integrate into the full panoply of AI techniques that have been developed over the past 50 years, from symbolic logic to intelligent agents to evolutionary algorithms. On the other hand, given the rate resources are now pouring into the field, it may be quicker.

Recently, Google company Deepmind put its AlphaGo program to the test. AlphaGo was the first program capable of playing the game Go at a professional level. A mere decade ago, as I described the situation in *Beyond AI*, “By contrast to chess, programs playing Go have yet to challenge even serious amateurs, much less the top professionals. ... [T]he connected clusters on the Go board are like the pieces in chess. But there are only six different kinds of chess piece; the number of different configurations of a cluster on a Go board is astronomical. So in playing Go, if you equate clusters to pieces, you have to be able to invent new pieces as you go, so to speak, and to infer the capabilities of the ones your opponent is inventing. Thus, at the moment, i.e. unless someone finds another cute trick that is a special case solution, playing Go well requires solving the real AI problem, that of creating useful concepts from experience.”

In other words, playing Go well requires the same kind of concept formation that was demonstrated by the deep neural net in climbing from character sequences to words, phrases, and sentences. You will not be at all surprised that AlphaGo contains not one but two deep neural nets, which are effectively integrated with a classical algorithmic game-playing program.

[\[258\]](#)

AlphaGo improved with shocking rapidity, beating a top-ranked human player, Lee Sedol, in a million-dollar challenge tournament in March 2016. Virtually every commentator understood the value of the technical innovation of the working combination of algorithmic search and learning neural nets. Many of them, however, seem to share the same ivory tower blindness my friend showed toward the DARPA self-driving cars challenge. AlphaGo is a scalable program, running on a cluster of up to 1920 CPUs and 280 GPUs. That allowed some people to denigrate the feat as “brute force,” and not so impressive from an algorithmic perspective. But in the real world, what is impressive is that AI researchers now have the resources to use whatever horsepower is necessary to the task, and the

know-how to deploy it effectively. In fact, it was revealed a little later that Google had built custom chips specifically to accelerate the deep-learning algorithms, which had given them about a half-decade jump on expected Moore's Law progress. Another interesting indication of the fact that AI is moving from academia to industry is that Deepmind's *Nature* paper has 20 authors. LinkedIn's 2017 Jobs Report tells us that the fastest-growing position is Machine Learning Engineer. I know of at least 225 AI/machine learning conferences scheduled in 2018. Perhaps the brothers Wright are gazing down with an amused sense of *deja vu*. We live in interesting times.

Robo Habilis

A human being should be able to change a diaper, plan an invasion, butcher a hog, conn a ship, design a building, write a sonnet, balance accounts, build a wall, set a bone, comfort the dying, take orders, give orders, cooperate, act alone, solve equations, analyze a new problem, pitch manure, program a computer, cook a tasty meal, fight efficiently, die gallantly. Specialization is for insects.

—Heinlein

In an interview a few years ago, Steve Wozniak of Apple fame opined that there would never be a robot that could walk into an unfamiliar house and make a cup of coffee. I feel that the task is demanding enough to stand as a *pons asinorum* for an embodied AI, *i.e.*, robot in the sense Asimov used the word.

A robot is placed at the door of a typical house or apartment. It must find a doorbell or knocker, or simply knock on the door. When the door is answered, it must explain itself to the householder and enter once it has been invited in. (We will assume that the householder has agreed to allow the test in her house, but is otherwise completely unconnected with the team doing the experiment, and indeed has no special knowledge of AI or robotics at all.) The robot must enter the house, find the kitchen, locate coffee-making supplies and equipment, make coffee to the householder's taste, and serve it in some other room. It is allowed, indeed required by the specifics of the test, for the robot to ask questions of the householder, but it may not be physically assisted in any way.

The state of the robotics art falls short of this capability in a number of ways. The robot will need to use vision to navigate, identify objects, possibly identify gestures (“the coffee’s in that cabinet over there”), and to coordinate complex manipulations. Manipulation and physical modelling in a tight feedback learning loop may be necessary, for example, to pour coffee from an unfamiliar pot into an unfamiliar cup. Speech recognition and natural language understanding and generation will be necessary.

Planning must be done at a host of levels ranging from manipulator paths to coffee-brewing sequences.

But the major advance for a coffee-making robot is that all of these capabilities must be coordinated and used appropriately and coherently in aid of the overall goal. The usual set-up, task definition, and so forth are gone from standard narrow AI formulations of problems in all these areas; the robot has to find the problems as well as to solve them. That makes coffee-making a strenuous test of a system's adaptiveness and ability to deploy common sense.

I claim that this test addresses the bulk of the aspects of general intelligence that are missing from AI today. Although standard shortcuts might be used, such as having a database of every manufactured coffeemaker built in, it would be prohibitive to have the actual manipulation sequences for each one pre-programmed, especially given the variability in workspace geometry, dispensers and containers of coffee grounds, and so forth.

Transfer learning, generalization, reasoning by analogy, and in particular learning from example and practice are almost certain to be necessary for the system to be practical.

Coffee-making is a task that most 10-year-old humans can do reliably with a modicum of experience. I would guess that a week's worth of being shown and practicing coffeemaking in a variety of homes with a variety of methods would provide the grounding and enough generality that a 10-year-old could make coffee in the vast majority of homes in such a "Wozniak Test." It is a good test of generality in a robot because, although it would be possible to hand-code most of the skills needed, it would be much cheaper simply to build a coffeemaker into the robot! Thus nobody would spend the resources necessary for the brute-force programming approach. The only economical way to do the task is to build general learning skills and have a robot that is capable of learning not only to make coffee but any similar domestic chore.

One of the species of early hominids is named *Homo habilis*, meaning "handy man," for their significant advancement in tool use over previous hominids. One of the goals of the AGI Roadmap [\[259\]](#) was to chart paths from the current state of AI to full human intelligence, and one of the paths might follow the one that evolution took. The Wozniak Test is a case of tool use competence. It turns out to be a special case of what we might call the

Nilsson Test, as outlined in a paper in 2005 by Nils Nilsson, one of the leading figures in AI:

Machines exhibiting true human-level intelligence should be able to do many of the things humans are able to do. Among these activities are the tasks or “jobs” at which people are employed. I suggest we replace the Turing test by something I will call the “employment test.” To pass the employment test, AI programs must be able to perform the jobs ordinarily performed by humans. Progress toward human-level AI could then be measured by the fraction of these jobs that can be acceptably performed by machines. Let me be explicit about the kinds of jobs I have in mind. Consider, for example, a list of job classifications from “America’s Job Bank.” A sample of some of them is given in figure 1:

- *Meeting and Convention Planner*
Maid and Housekeeping Cleaner
Receptionist
Financial Examiner
Computer Programmer
Roofer’s Helper
Library Assistant
Procurement and Sales Engineer
Farm, Greenhouse, Nursery Worker
Dishwasher
Home Health Aide
Small Engine Repairer
Paralegal
Lodging Manager
Proofreader
Tour Guide and Escort
Geographer
Engine and Other Machine Assembler
Security Guard
Retail Salesperson

Marriage and Family Counselor
Hand Packer and Packager

Just as objections have been raised to the Turing test, I can anticipate objections to this new, perhaps more stringent, test. Some of my AI colleagues, even those who strive for human-level AI, might say “the employment test is far too difficult—we’ll never be able to automate all of those jobs!” To them, I can only reply “Just what do you think human-level AI means? After all, humans do all of those things.”

Now some of those jobs require specialized training and years of experience, while some of them are entry-level, accessible immediately to the average human. Most are somewhere in between. Likewise, some of these jobs could be done today by robots, or at least mostly done; but in general the ones that can be are the simplest jobs, and today’s robots who can do even such prosaic things as climb stairs are multi-million dollar development projects, not mass-produced appliances.

We appear to be within striking distance of human brain-equivalent hardware now, but a very rough estimate is that in current technology it would weigh literally a ton, use 50 kW of electricity plus a matching amount of cooling, and cost about a million dollars. Another decade or two of Moore’s Law will change this, but in that timeframe Moore’s Law implies nanotech. It seems quite reasonable from a purely technological standpoint to expect intelligent humanoid robots and fast VTOL flying cars to cost (very roughly) the same for the foreseeable future.

Today’s human-equivalent machine would not threaten jobs directly but threaten to produce skilled assistants that could allow fewer people to do more. Jobs are going to continue to be progressively automated, with people becoming more productive but still necessary, in the same way jobs have been since 1700.

The forward step in AI represented by AlphaGo does not imply a comparable advance in physical robotics. One of the main components of the surge in efficacy of deep-learning neural nets was the availability of enormous amounts of data on which to train them. For language machines this means things like the literally millions of books and other textual data and audio available online; for AlphaGo it included the historical record of

human games played (the earliest recorded game was in AD 250, but substantial numbers of game records only go back about 500 years). In addition, AlphaGo played millions of games against itself in the process of learning.

This works much better for a simple, well-defined, digital environment such as a board game—a typical game of Go can be compressed into about 237 bytes, [\[260\]](#) and a chess game into less than 100—than in the boisterous, messy, expensive real world. Ironically, in the same week that Google’s Deepmind company won with AlphaGo, they put their robotics company, Boston Dynamics, up for sale. Gary Marcus, CEO of AI startup Geometric Intelligence, quipped, “Rosie the robot, you can’t have it knock over your furniture a hundred thousand times to learn.” [\[261\]](#)

The bottom line is that we are only at a glimmering of the dawn’s earliest light of the Age of Robots. But I would say we can see enough that failing to expect them has changed from a Failure of the Imagination to a Failure of Nerve.

The Rising Tide

Those were terrible days for the Americans. They were hunted like wild beasts. Only those survived who finally found refuge in mountains, canyons and forests. Government was at an end among them. Anarchy prevailed for several generations. Most would have been eager to submit to the Hans, even if it meant slavery. But the Hans did not want them, for they themselves had marvelous machinery and scientific process by which all difficult labor was accomplished.

—Philip Francis Nowlan, *Armageddon: 2419 A.D.*

These new machines have a great capacity for upsetting the present basis of industry, and of reducing the economic value of the routine factory employee to a point at which he is not worth hiring at any price. If we combine our machine-potentials of a factory with the valuation of human beings on which our present factory system is based, we are in for an industrial revolution of unmitigated cruelty.

—Norbert Wiener

The Jetsons was a caricature of 1960s-era life, and thus left unexplored many of the implications of the trends it depicted. But consider: Rosey was easily smart enough to do everything that Jetson did at work. Why didn't Spacely Sprockets simply buy Rosey instead of hiring George? In real life, of course, this is essentially what has happened. We haven't replaced all our workers with robots, but in the manufacturing sector, we've replaced 85% of them. Since the industrial revolution, advancing technology has been making it possible for fewer and fewer people to produce more and more stuff.

Back when George Washington was President, virtually everybody in America (and everywhere else in the world) had to work on a farm just to produce enough food to live. Each farmer only produced enough food for 1.1 people. But as technology improved, farmers became more efficient, and each farmer now feeds 40 people. There does, of course, need to be

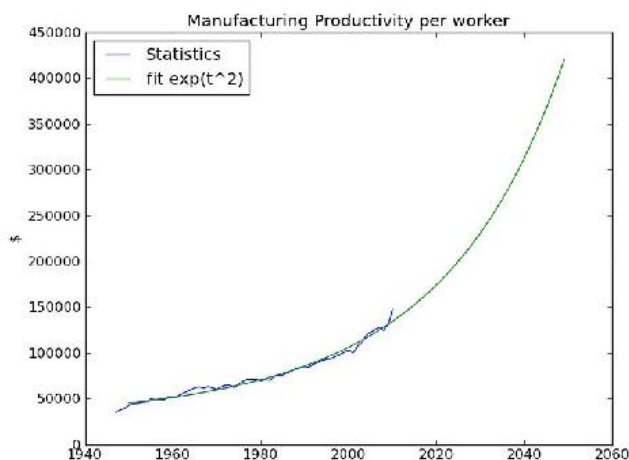
industry to produce the machines that modern farmers use. But the same phenomenon, and trend, can be seen in manufacturing: In the 1940s, over a third of jobs in the US were in manufacturing; now less than 9% are.

The number of manufacturing jobs per capita has declined steadily since WWII, just as have the farm jobs. This is not because industry is producing less, or that jobs have been going overseas, as is sometimes claimed; domestic American factories produce three times as much total goods as they did in 1950. Output might have risen faster without offshoring, but it certainly did not decline.

But there's another way of looking at the manufacturing statistics, that is similar to the way we look at the way each farmer feeds 40 times as many people as before. In manufacturing, the number of workers went down and the output went up—and the output per worker went way up. Each manufacturing worker in 1962 produced about \$25,000 (in constant 2010 dollars) worth of output; in 2012 each worker produced \$160,000 worth.

[\[262\]](#) It may help to remember that this includes not only the assembly-line workers, but foremen, engineers, QA specialists, accountants, managers, and lawyers—everybody who works for a manufacturing company.

Productivity is clearly on an exponential increase; in fact, if you fit a curve to the data, you get a curve that is slightly hyperexponential: [\[263\]](#)



If things keep up at that rate, by 2062 the average worker in manufacturing (George Jetson, for example) would produce \$661,000 in value per year.

Note for comparison that the average employee of Apple Computer in 2012

already produced \$400,000 in value; so did the average Lockheed-Martin employee. Over the latter 20th century, workers have gotten paid about 64% of the value added, with the rest going to taxes, capital equipment, dividends for stockholders, and so forth. At this rate Jetson makes \$423,000 in 2062. (Although if we stay with the same roughly 3% inflation rate we've averaged since the 80s, he will call it \$1,854,392.) The hyper-exponential nature of the fit, though slight, is significant. In a pure exponential growth curve, the year-to-year percentage increase is fixed. With the hyper-exponential, it increases. In 1962, a manufacturing worker was 1.1% more productive each year. By 2062, Jetson would be 3.7% more productive each year. Add this to the cumulative nature of the curve and the result is startling: in 1962, the average worker produced \$734 more than in 1961. In 2062, Jetson produces \$23,562 more than in 2061.

What's My Line

The big issue is not really jobs, but incomes. If you have an income, then many people would be happy to lose the job.

—Martin Ford

Interstate highway I80 runs just about 3000 miles from New York City to San Francisco. The population of the United States is (very roughly) 300 million people. Line the people up along I80; give them a square yard apiece and they will cover the whole 180-foot-wide right-of-way for 100,000 people per mile. Now what we are going to do is to line them up in order of economic productivity—assuming they work full-time—most productive in New York, least in San Francisco. Which actual aspects of a person put him at what point along the highway will of course vary with the level of technology: in 1790 it was important to have physical strength, manual dexterity, and a talent for handling animals; today the ability to pore over columns of figures for hours on end is more useful.

The point of the exercise is as follows: we want to find the point where, with a given technology, you would have to separate workers from non-workers if you wanted to have the fewest people working in the given economy. Obviously you would employ the most productive, since that way

you get the most output from the fewest people. You employ everyone to the east of your chosen point. A second factor is the total amount of consumption you wish to have in the society. It makes no difference for this exercise how this consumption is distributed among the population, so we will completely ignore that question.

In 1790s America, as indeed in any society in the world up to that time, virtually everybody had to work to maintain just a subsistence level of consumption. If 90% of workers were farm workers, there weren't too many people left to be butchers, bakers, and candlestick makers. In reality, of course, much of that kind of work, as well as everything from weaving to soapmaking, was done on the farm, and much of it by women and children who aren't counted in the worker statistics. But it is probably a fair estimate that at least 90% of the population would have to work at a 1790s technology level to provide that subsistence level of consumption to all. That means everybody standing along I80 outside of California.

So here's an interesting question: where would the cut be on the chart if we substituted the technology of today, but kept the consumption levels of 1790? We've noted that each farmer today feeds 40 people instead of 1.1, but a surprising number of today's farmers either don't provide subsistence level food or don't use the best technology. A real-world example, not far from my house, is an organic lavender farm. What is more, Americans today eat a lot more, and more varied, food than our ancestors did in 1790. Thus I feel safe in guessing that for a chart with 2015's technology but 1790's consumption, the cut would be somewhere in the neighborhood of two percent. Call it half as many farmers as we actually have, and the same number in industry producing sophisticated machines for the farmers and candlesticks for everyone else. Only the people standing in New Jersey would have to work in such a world. In other words, an industrial cadre of just 6 million (with whatever capital they needed) could feed, clothe, and shelter the rest as well as the average American had been in the Washington administration. (Do remember that the 6 million are, by assumption, the best, brightest, most talented, and hardest-working people the country has to offer.) Why, then, is the unemployment rate not 98%?

The answer is almost as blindingly obvious as it is blandly ignored in discussions of future productivity gains: it's because we want more than they had. We want not only trains but cars for everyone, a great highway

system, and easy jet travel to anywhere in the world. We like being able to take pictures of our children. We value having penicillin instead of dying of strep throat as George Washington did. We like central heating and air conditioning and not having to build a fire in the wood stove. We appreciate barramundi and mahi-mahi and Patagonian toothfish. [\[264\]](#) We desire not only the occasional handbill, but books, newspapers, magazines with colored pictures, radio, television, movies, and the Internet. We think of baths, indoor toilets, underwear, deodorant, and shampoo—not to mention smartphones—as necessities of life.

This is far from a novel observation. In 1933 John Maynard Keynes blamed unemployment on “our discovery of means of economising the use of labour outrunning the pace at which we can find new uses for labour.” The obvious solution would have been finding new uses.

The interesting thing is that throughout the Nineteenth Century and half of the Twentieth, the cutoff point stayed more or less at 90%. In 1950 the male labor force participation rate was still over 85%, and 95% for healthy men aged 25 to 50. As of even date it has dropped to about 70%. This is, for a ballpark estimate anyway, a usable proxy for the cutpoint in our thought experiment. Nobody standing in California, Nevada, Utah, or half of Wyoming would have to work. (The female labor force participation rate is not a reasonable proxy, since before the Fifties, women typically did as much work as men but were not recognized as part of the formal economy, so changes in female labor force participation rate don’t reflect actual changes in the amount of work women were doing. Today, the total official labor force is currently 50% of the population—think North Platte, Nebraska.) One could claim that up until 1950 or so (with the exception of the Great Depression), the US had the cutoff at approximately Reno, after which it started sliding towards the east. In 1940, manufacturing amounted to about 30% of the U.S. jobs (people standing in Illinois, Indiana, Ohio, Pennsylvania, and NJ), but by 2010 it had fallen to 8% (east of Punxsutawney, PA). [\[265\]](#) Meanwhile, as we have seen, output per manufacturing worker increased by a factor of 6. But the output of the economy over all, the GDP per capita, only increased by a factor of 3. It would probably be a fair guess that we are halfway between the extremes now.

Do What

There are about 3.5 million truck drivers in the country—call it everyone standing on I80 between New York and Parsippany, New Jersey. In many states, truck driver is the most common single typically-male job (For comparison, there are 2.5 million waiters and waitresses). Much has been made of the prospect of self-driving trucks and the threatened obsolescence of these jobs. If we look at the reality of the problem, though, it begins to look like any other automation process. Trucks still need to be loaded and unloaded, dispatched, and scheduled. A truck making local deliveries isn't likely to be automated until we get full-fledged humanoid robots. There are actually 9 million people in the trucking industry total.

Furthermore, there are well over a million separate trucking companies. A truck owner/operator won't be put out of business by having a self-driving truck; he'll just work less for the same income, or make more for the same work. The bottom line is that even with self-driving trucks, the industry will become more efficient in much the same way manufacturing has, with each person accounting for more freight miles.

Trucks move about 10 billion tons of freight in the US each year, or 30 tons per American. If productivity doubled, we could either fire half of truckers or move twice as much stuff with the same human effort. This has happened many times over on the technological path from oxcarts to containerized multimodal freight, and there's no reason to expect it to stop. There's also no reason to think it's something new and disruptive.

In 1800, more than 85% of people lived in what we would consider extreme poverty, Level 1 on Rosling's scale, unable to afford even shoes. Now, for the first time ever, according to the World Bank, that figure is in single digits: 9%. This is because of machines, because of increasing productivity, because of automation. The sooner the last of the starving-dirt-farmer jobs are gone, the better.

If we let machines put us out of work, it will be because of a failure of imagination and the will to make a better future!

—Tim O'Reilly

——Bottom Line——

The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom.

—Isaac Asimov

It's a low bar.

—(machine ethicist) Ronald Arkin

Let us suppose that we can build, say in 2030 or 2040, a doctor robot as good as an average human doctor. As the price of computation falls, we can combine the general practitioner with more and more specialists, until we have something with at least a superhuman breadth of knowledge. We can also improve the speed of its thinking, and very likely we [\[266\]](#) will learn enough more about the process of thought to push it up towards the high end of the human range of intelligence. It's not at all hard to imagine that we could have a doctor with encyclopedic expertise, instant built-in access to all the latest research, and an effective IQ of 200. Oh yes, and it doesn't get tired or make mistakes.

Even if it isn't cheaper, that is the doctor I will be going to—or more likely, who is coming to make a house call by downloading into my own service robot. Similarly for my lawyer and my tax accountant. I want a robot architect to design my house, a robot investment counselor, and robot engineers to design my flying car.

One of the reasons that we have stumbled moving from Level 4 of wealthiness to Level 5, is that we don't have a clear idea of the advantages it could bring us. Yes, a flying car will allow you to have dinner in Paris with the same convenience you now go to Poughkeepsie, but is that life-changing? On the other hands, robots are likely to make a huge difference, whether it be a higher level of competence among professionals, or an affordable housemaid for the masses, *a la* the Jetsons' Rosey. Self-driving cars, the current fad *du jour*, are the equivalent of everyone having their own chauffeur; we will each have a full domestic staff by the end of the

century. Add to that the physical productivity of nanotech, and you really do get a significant quantum jump in the quality of life.

A Cleaner, Better Breed

There is another reason that we want robots instead of people in positions of trust and responsibility, summed up in the word “reliability.” The robot works 24/7; the robot doesn’t take vacations or family leave or get sick. The robot will not sue you for hiring bias or sexual harassment. It will not harass your other employees, causing them to sue you. Most importantly, the robot will not steal from you. Employees steal about \$50 billion from American businesses each year, causing about a third of business bankruptcies. [\[267\]](#) If you want to understand the essence of machine ethics, simply imagine that you have managed to design and program a robot that can perform the tasks of a salesclerk in a retail store. How much extra work must you do to improve it to the point where it won’t steal from the store? The answer, of course, is: None.

What are the chances we might actually manage to produce what Benjamin Franklin called a “moral Science” that works as well as our physical technology? I do not think it impossible. I spent an entire book (*Beyond AI*) arguing that if we can make robots smarter than we are, it will be a simple task to make them morally superior as well. Asimov thought so too: “They’re a cleaner, better breed than we are.” Because you are a product of evolution, your design includes the legacy of every scheming monkey, vicious shrew, and fratriphagic fish in your ancestry, who beat out their brethren in an unbroken billion-year existential succession. To build a better robot, we need only copy the “thin veneer of civilization” at the top; a good robot is a lot simpler than a human-like one.

Surprisingly enough there is good reason to hope that surrounding ourselves with smart, highly moral robots will improve the morality of humans as well. There are two forces in play: the first is that people tend to adapt themselves to the ethic of their community, and judge their own behavior by that of their fellows. The second is simply that the smarter everyone else is, the harder it is to cheat. Even in the throes of self-deception, people subconsciously adapt their behavior, like their fish stories, to what they think they can get away with.

One of the harder jobs that humans do, some well and some poorly, is management of other humans. One of the major reasons this is hard is that humans are selfish, unreasonable, fractious, and just plain ornery. It will be some time, I suspect, before the state of the art is good enough to produce robot managers that are as good as human ones: humans have a lot of poorly-understood intuitive mechanism evolved to deal with other humans. On the other hand, managing robots with human-level competence will be falling-down easy. In the next couple of decades, robots will be climbing up the levels of competence to compete with human workers at one job and another. Until they become spectacularly better, though, I suspect that the major effect will be to make management easier—perhaps so easy a robot could do it!

Once we build trustworthy IQ 200 machines, only an idiot would trust any human to make any decision that mattered, or want a human in any position of responsibility. Clarke in *Profiles*: “... the automobile of the day-after-tomorrow will not be driven by its owner, but by itself; indeed it may one day be a serious offense to drive an automobile on a public highway.”

What then are we humans supposed to do?

Don’t look at me! We already know that only a fool would ask a human such an important question. Ask the machines.

We can only see a short distance ahead, but we can see plenty there that needs to be done.

—Alan Turing

23 Engineers' Dreams

Clearly then you must also be ignorant of the fact that the Clouds are also patrons of a varied group of gentlemen, comprising: chiropractors, prophets, longhairs, quacks, fops, charlatans, fairies, dithyrambic poets, scientists, dandies, astrologers, and other men of leisure. And because all alike, without exception, walk with their heads among the clouds and base their inspiration on the murky Muse, the Clouds support them and feed them.

—Aristophanes, *The Clouds* (423 BC)



Sunset over Mo'orea, seen from Fa'a'a.

It is, as I write, 81 degrees in Fa'a'a, on the western shore of Tahiti; the expected high for the day is 89. Halfway up the slopes of Mont Orohena, it's 70 or so because of the adiabatic lapse rate of temperature with altitude. Even on the surface, Tahiti is comfortable year-round if you are in the shade, although direct sunlight in summertime is a different matter. Temperatures across the tropical Pacific are similar; the islands are considered a slice of paradise for good reason. There is easily ten times the area of the US in the tropical oceans, and all of it has a climate like Hawaii. What I would really like to do, though, is float along over the ocean at about 3000 feet in an open-decked airship, *mai-tai* in hand, watching the endlessly fascinating cloudscapes, the spectacular sunsets, and being wafted from island to island by the trade winds. Imagine an airship, or rather airborne village, whose gasbag consisted not of a few big balloons in a fish-shaped cover, but a cluster of a billion or so small balloons (10 cm would give a gram of lift apiece), randomly spaced

and tied together by invisibly thin diamond thread. (Diamond thread the width of a bacterium, i.e. half a micron, should be about right.) The whole business could be made to look, from any reasonable distance, like an actual natural cloud.

Below this hangs, perhaps by structures that look like tall trees, shaded from the tropical sun by the “cloud,” a village of terraces, courtyards, and esplanades. A center is connected by walkways, while private residences are typically reached by wearable folding powered wings. Given the nanotech necessary to build the whole cloud city and the wings in the first place, it seems not unlikely that they could be made to look like great white bird wings. It seems much less likely that the inhabitants would be interested in wearing robes or playing harps, however. I wouldn't.

No visible means of support

I'd settle for flying cars. But they need to be real flying cars with antigravity or reactionless thrusters, not ducted-fan kludges.

—Glenn “Instapundit” Reynolds

In *Profiles of the Future*, Clarke listed in his future timeline the invention of a “Space Drive” somewhere in the 2050s. “It is an act of faith among science fiction writers, and an increasing number of people in the astronautics business, that there must be some safer, quieter, cheaper, and generally less messy way of getting to the planets than the rocket.” A space drive, or reactionless thruster, is something that science fiction has often posited as not only an enabling technology for spacecraft but for flying cars. Gravity is not completely understood; if you ask a cosmologist, you will discover that the universe is thought to consist of 5% normal matter, i.e. stars and planets, and 95% “dark energy” and “dark matter.” “Dark” in these phrases means that we can’t observe them and don’t know what they actually are. We just assume they’re there because our best theories of gravitation don’t match what we actually see the normal matter doing. Is there new physics to be discovered in the field of gravity? Almost certainly. Will this give us a technology of antigravity? I have no idea.

Gravity is by far the weakest of the known forces of physics, less than the electromagnetic force by a factor of a trillion trillion trillion. Surely we should be able to find some very tiny third, fourth, or fifth-order effect of electromagnetism that could trump gravity! Indeed, the Van der Waals “force” that makes atoms sticky is such a second-order effect.

We don’t know what we will be able to do when we are able to play with really strong magnetic fields. It turns out that you can suspend a live mouse in a 17-tesla magnetic field, as the field interacts with the diamagnetic properties of the water in the mouse’s cells. Similarly, you can attract liquid oxygen to a magnet because it is paramagnetic. You could in theory cause an increase in pressure in the air with a field in the hundreds of tesla range, although it would wreak havoc on pretty much anything else.

In the meantime, of course, we can suspend trains with magnetic fields we can generate and control now, though their altitudes are measured in millimeters.

We don't know a way to levitate a car using magnetic forces at the altitudes of interest to us, but we certainly don't know that it is impossible.

Space Drive

The main problem with reactionless thrusters is not so much that some smart person hasn't managed to invent them yet, but that they are completely incompatible with generally accepted physical law. Unlike cold fusion, where the energy is available according to standard physics if we could only figure out a workable pathway, a space drive flat-out violates the conservation of momentum. Conservation of momentum is such a basic part of the laws of physics as currently understood, that the math (Noether's Theorem) tells us that if it isn't universally true, then we can't even expect the laws of physics to remain the same when we do an experiment in a different place (i.e. to remain symmetric to space translation).

It is then purely in the spirit of trying to avoid Failure of the Imagination that I, gathering with frail and failing hands the tattered shreds of my scientific credibility, examine the possibility that we might actually get a space drive any time soon, or ever. Even so, the only reason that I feel justified even mentioning it is that there has been published a peer-reviewed paper in a reputable journal [\[268\]](#) by NASA experimenters claiming exactly that.

The EM Drive, invented by Roger Shawyer in 1999, is conceptually quite simple. It consists of a frustum (truncated cone) of electrically conducting (and thus microwave-reflecting) material, with flat ends. An office trash can, if it had a flat lid, would approximate the shape. The test article in the experiments was 9 inches long, 11 inches across on the big end, and 6 inches across on the small end. There was a 2-inch thick slab of polyethylene fitted into the small end. In operation one directs a stream of 1.9 GHz microwaves to bounce back and forth between the ends, setting up a standing wave pattern with two nodes along the axis of the cone and 4 across. This is supposed to generate a thrust toward the big end.

40 W	60 W	80 W
48	106	76
30	91	119
53	128	117

Measured thrusts, in microNewtons, at three power levels and three different electronic control system tunings. Precision is $\pm 6\mu\text{N}$ in all cases.

The tests were carried out in vacuum, with fairly elaborate precautions taken to prevent a wide range of possible confounding factors. The instruments had rated measurement precision in the nanoNewtons, 10,000 times smaller than the actual measurements. Even so, the measured thrusts are tiny: if you could somehow scale it up to high power at the best thrust-to-power ratio achieved, you would need 2.2 megawatts (3000 horsepower) to produce a pound of thrust. Even so, the thrust is three orders of magnitude higher than a photon rocket, producing 1 to 2 $\mu\text{N}/\text{W}$ compared to 3 to 6 $\mu\text{N}/\text{kW}$. This is one reason that the authors are confident that the thrust is not due to a leaked radiation effect. On the other hand, it is about a factor of 50 less than a Hall thruster (ion rocket), but of course the Hall thruster uses reaction mass.

What can possibly be going on? By far the most likely explanation, of course, is that someone made a mistake, either in measurement, or in not excluding some perfectly conventional effect, or the like. 100 nanoNewtons is the sideways force you get on a 10-pound weight when you put it on a frictionless surface tilted by one inch per the diameter of the Earth. By far the *least* likely explanation is that the the EM Drive really is a reactionless thruster in the basic physics sense. If there is any daylight at all between these extremes, it would have to be that there is something against which the thruster is getting traction: dark matter, perhaps, or the mass/energy implicit in the quantum field.

Once upon a time, I had the opportunity to listen to an artist who made bells of glass. These were quite beautiful and produced the same tinkling sounds you would expect. For contrast, he had also made similar bells out of pure quartz: the same silicon dioxide substance, but a crystal instead of the

disordered molecular structure of glass. The quartz bells rang with a pure tone that went on, and on, and on—audible perhaps ten times longer than the glass ones.

An electronics engineer would have said that the quartz bells had a higher Q factor than the glass ones. Q in a resonator is a measure of how fast energy at the resonant frequency dissipates out into other frequencies and is lost. The EM Drive is essentially an electronic bell. The higher the Q, the better the efficiency of force produced per watt of input power, according to Shawyer's theory. Note that Shawyer's theory may not be the right one even if the device does produce thrust; but the part about the Q factor seems much more reasonable than the rest of it. Shawyer's (and NASA's) copper, almost steampunk-looking, experimental machine has a Q of 35 thousand; the state of the art in superconducting microwave resonators used in particle accelerators, for example, is 50 billion. Call it a factor of a million better efficiency.

If this turns out to be a real effect *and* Shawyer's theory turns out to be right—and we are going far afield into la-la Failure of the Imagination land here—we should expect to be able with nanotech to build atomically precise, optical frequency thrusters that get on the order of Newtons per watt. In which case your two-ton flying car is supported against gravity by a 30-horsepower engine.

The perspicacious reader will instantly smell a rat. If we put the same thruster in only a *one*-ton car, the car would accelerate upward at one G (its occupants experiencing 2G), gaining energy at a rate that would very quickly surpass 30 HP. Well, no. Even Shawyer's theory says the effect disappears with acceleration. But Einstein tells us that gravity and acceleration are the same; maybe the gadget can't even work against a gravity field? After all the experiments, as far as I know, were all done with the gadget (a) standing still, and (b) oriented sideways to the local gravity. One might imagine it being used to maintain a static force, e.g. to overcome air resistance, when following an orbit-like path. But even that quickly runs afoul of the conservation of energy, given the heat being dumped into the air. So it is quite difficult to conceive of a law of operation for the EM Drive that is both consistent and useful.

[Added in press: a later set of experiments makes the “they made a mistake” explanation of the effect look a lot more probable. [\[269\]](#) My faith in physics

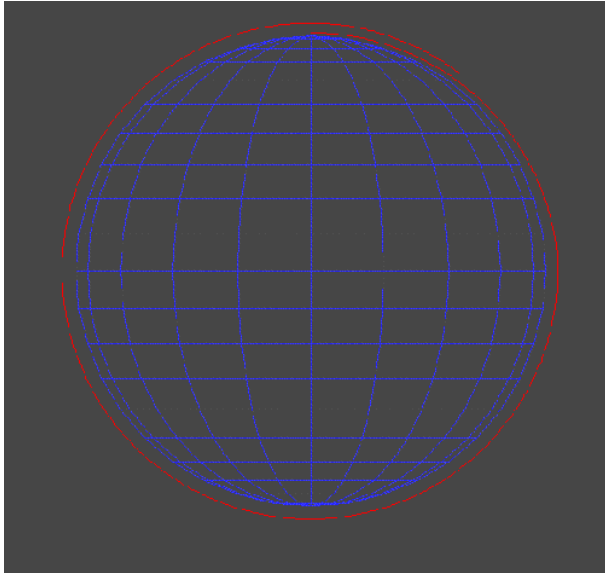
is restored.]

The other “space drive” currently being looked at is called the Mach Effect thruster (sometimes called the “Woodward Effect” after its inventor). This is another device which has been claimed to have been tested in the laboratory, both in original experiments and in replications, producing thrusts in the microNewton range. As with the EM thruster, these are so tiny that it is very hard to rule out experimental error or unanticipated second-order effects.

The Woodward drive has somewhat more congenial theoretical antecedents than the EM. It is based on Mach’s Principle, which is a theory of inertia that formed the conceptual springboard for Einstein’s theories of relativity. The basic idea is that adding energy to a mass increases its inertia. If you can vary the inertia of something, you can push it while it is heavy and pull it back while it is light, obtaining on the average an unbalanced push. The Woodward thruster is a stack of piezo-actuators which accomplish both the addition of the potential energy and the pushing. Recently published analyses [\[270\]](#) indicate that the force is proportional to the sixth power of the frequency. The frequencies used in the electro-mechanical device are in the kilohertz; if we could go to megahertz in a nanoscale device we might obtain significant thrust. If the effect is real, the theory is correct and extrapolates validly, and so forth *ad practically infinitum*.

How likely is any of this to be real? I would have to put it down in the low single-digit percents—but that does not mean we shouldn’t be pursuing it. It means we should be pursuing hundreds of things like it.

Space Pier



A payload launched from a space pier at 8km/s, launch altitude 100 km, corrected to a 340-km orbit.

It is a good idea at this point, however, not to forget where the boundary between the Failures of Nerve and Imagination lies, particularly in so far as flying cars are concerned. So let us take a big step back across it from the impossible to the possible. Let's look at what Second Atomic Age technology could do—could be doing now if Feynman's path had been taken—to make space travel more achievable and affordable. It's widely understood how lighter, stronger structures can make rockets more efficient, but that's of limited use. The rocket equation is still a huge stumbling block. One way around the rocket equation is not to use rockets at all. With nanotech we could easily build a space pier.

The idea of a space pier is just the same as for a pier for ordinary boats: it bridges the gap between the land and the regime where the ships operate. In the case of water ships that's water of a certain depth; in the case of spaceships it's vacuum and orbital velocity.

Build a structure 100 kilometers tall and 300 kilometers long. Due to the curvature of the earth the center is bowed nearly 2 km away from a straight

line; the accelerator track on the top is nearly 5 km longer than the base (even though both end towers are locally vertical). The tower extends completely through the stratosphere (50 km) and mesosphere (90 km) extending into the ionosphere. Put a linear induction (or other electromagnetic) motor along the top. An elevator goes straight up 100 kilometers to the starting end. Payloads are then accelerated horizontally into orbit with an acceleration of only 10 G's (which appropriately cushioned humans can stand for the 80 seconds required). This hybrid approach overcomes the drawbacks of both the typical orbital tower schemes (it's less than 1% the height of a skyhook, and doesn't drag the passengers at slow elevator speeds through the Van Allen radiation belts) and ground-based electrolaunch ones (air resistance at 100 km is a million times less than at sea level).

Like any other launch-track-based scheme, this has the huge advantage that you're only accelerating the payload, instead of ten or twenty times the payload's mass of fuel and oxidizer, to orbital velocity.

Compared to the skyhook (geostationary orbital tower), which is just barely possible with even the theoretical best material properties, a tower 100 km high is easy. Flawless diamond, with a compressive strength of 50 GPa, does not even need a taper at all for a 100 km tower; a 100-km column of diamond weighs 3.5 billion newtons per square meter, but can support 50 billion. Even commercially available polycrystalline synthetic diamond with advertised strengths of 5 GPa would work. Of course in practice columns would be tapered so as not to waste material; and the base of the tower would be broadened to account for transverse forces, such as the jet stream. Only the bottom 15 km (i.e. 15%) of the tower lies in the troposphere and would have to be built taking weather into account.

The electromagnetic accelerator along the top might be fairly heavy. In many designs, coils have iron cores; NASA's Marshall prototype weighs 100 pounds per foot. If we allow a tonne per meter, the total weight of the accelerator is 300 thousand tonnes. For comparison, the Golden Gate bridge is about 800 thousand tonnes. However, most the weight is (relatively cheap) iron. In fact, even if we had a lighter material available, we might build the track heavy anyway for stability. Note that this entire weight, if it were concentrated in one place, could be supported by a column of currently available polycrystalline diamond less than 80 centimeters on a

side. The overall structure could be openwork like a radio tower, and might have approximately 60 footprints 10 km (30 long x 2 wide) apart on the ground—if we set aside a hectare for each foot, they only occupy 0.02% of the land under the tower. The footprint foundations would each bear the weight of a small office building, no great technical challenge. One of the interesting challenges in designing the structure is that simple diamond columns only thick enough to support its weight would be much too thin to be rigid. Two strategies which can be brought to bear are truss structures and thin shells inflated for stiffness.[\[271\]](#) At altitudes below the tropopause, some attention should be paid to reducing the structure's wind cross section to minimize the effects of hurricanes and the jet stream.

Another connection to the Feynman Path, beyond simply needing nanotech to start with, is that the construction of the tower would be facilitated by tele-operated scale-shifting robots, this time to larger scales, instead of having people in spacesuits crawling around 60 miles up in essentially vacuum.

The reason for the 60-mile (100 km) height is that it's just the edge of space. The air is about a million times thinner than on the ground, but there's still enough of it that nothing orbits at that height. A major problem with a scheme like a space elevator is orbital junk; the elevator stalk is virtually guaranteed to be hit. Remember that anything in orbit carries about 30 megajoules per kilogram in kinetic energy; for comparison, TNT provides only 4.6 MJ/kg. The pier is low enough that the orbit of anything at that altitude decays relatively quickly.

The tower would be maybe a million tonnes of material in a structure 300 km long. A typical superhighway that long involves 15 million tonnes of material and costs on the order of 1 to 5 billion dollars. Assuming the land under the tower does not lose too much value (and it might well gain it, especially near the embarkation port), the area occupied by the footprints is trivial. The major obstacle to construction is likely to be legal hassles, not anything physical.

If the coils and electronics for the accelerator cost \$1000 per meter, total for the accelerator is under half a billion. The wildcard is the cost of the diamond (and the ability to fabricate it into structural beams). Diamond is a bit expensive today! If an Apollo-style (and -cost) project could do for diamond what the original one did for electronics, we could build the tower

in the next decade or so. Depending on the level of nanotechnology, diamond might cost \$100/kg like graphite for golf clubs and tennis racquets. Diamond costs much more than that today but there is no mass production—no one is using it as a structural material. A mature nanotechnology with a self-replicating technology base would push cost toward the cost of inputs; carbon in the form of coal can be had in quantity for as little as \$0.02/kg.

Note also that diamond isn't strictly even necessary; a number of modern materials ranging from inflated kevlar-polyethylene tubes to carbon-nanotube-filled aluminum would work.

The energy cost of sending a 10-tonne payload to the top of the tower by elevator is about 10 GJ (2778 kWh or \$138.89 worth of electricity at 5 cents per kWh), which amounts to 1.4 cents per kg. At an express elevator speed of 50 m/s (108 mph) it takes over half an hour to get to the top. It is not clear that there is a compelling reason to go faster, since, unlike rockets, elevators can be made efficient at as slow a climb rate as desired.

Inert freight would presumably have been packed into projectiles on the ground, but passengers would want to wait until getting to the top. (Nice view! The horizon is over 1000 km away. We should probably put a revolving restaurant up there.) At 10 G's launch acceleration, passengers will be best off ensconced in form-fitting, fluid-filled sarcophagi. Even so the launch will not be particularly pleasant.

The vehicle is then accelerated at 10G along the top of the tower for 80 seconds to 8 km/sec. The track is level and with no lateral acceleration the vehicle is in an orbit with a 100-km perigee and 500-km apogee. (The numbers include an assist from Earth rotation.) The energy required is 300 GJ (\$4166 worth of electricity, again for a 10 tonne payload), i.e. 42 cents per kg. Of course, there will be inefficiencies in the conversion of electricity to kinetic energy, so real electricity costs will be higher. The power (as opposed to energy) requirements average 3750 MW for the 80 seconds. The tower's power draw increases linearly from 0 to 7500 MW during the 80 seconds of a launch; a typical suburb on the same land might draw a peak load of 750MW. Local short-term energy storage, in a form conducive to rapid drawdown, will be necessary for load averaging. Energy storage (and release) requirements are constant per track length and amount to 1 MJ per meter. (1 MJ is the energy 15 pounds of lead-acid batteries, an ounce of

butter, or a speck of uranium the size of a grain of salt.) It might even be possible to store energy in the magnetic fields of the accelerator coils. Drawing at a typical power station's production of 1000 MW it would take 5 minutes to recharge the tower.

A single (10-tonne) payload launch would come to about \$4300 in electricity (43 cents/kg). If we estimate maintenance and operating staff costs as similar, operating costs might be about a dollar per kg. Note that the cost to higher orbits goes up linearly rather than exponentially as with rockets (within certain bounds). The other major part of the cost of a launch is amortization of the cost of the tower. If we can launch once an hour (and at an interest rate of 8%) we must charge \$0.91 per kg per billion dollars of tower cost. If the traffic is there the rate might be increased (and the cost reduced) by a factor of 10 but not 100. (NB: as payload size is increased, power costs go up per launch but not per kg; amortization costs go down per kg; and more kinds of things can be launched in one piece. The main limit is the accelerator. Chances are you could build one to handle 10 tonnes, but that's a guess.) Your payload needs to be a spacecraft capable of some 330 m/s delta-V to circularize its orbit. The best strategy is to inject into an orbit whose energy is the same as the desired circular one, and do a correction at the point the orbits cross which only changes direction. This is not a Hohmann transfer orbit, which optimizes total delta-V. With the launch tower, delta-V at correction is considerably more expensive than at launch, so we minimize it preferentially. Even so, given typical chemical Isp's, propellant for correction is some 10 to 15% of gross vehicle weight. (If it were a high-Isp direct fission rocket, of course, it would be trivial.) For freight that can be a cheap one-shot strap-on solid rocket. For passengers the vehicle needs to be re-entry capable in case of accidents, and is more expensive.

One way to gauge the economics of the space pier is to note that the current rocket-launched cost to orbit is \$10,000/kg. [\[272\]](#) At about a dollar/kg per billion of capital cost, one might claim the tower would be economic at anything less than \$10 trillion. However, this would require a market for launches at that price which does not exist. So it would be critical to lower the price to the point that there is a market with sufficient volume to keep the tower busy. Molecular manufacturing, even of a fairly unsophisticated form, could make it economical. Suppose means were found to manufacture

diamond and graphite fiber of 5 GPa compressive and tensile strength respectively, in quantity, at \$10/kg. If the structure needed half a million tonnes of material it comes to \$5 billion. Then the whole business might cost \$10 billion. (For comparison, the space station is costing \$20 billion and Apollo cost \$24 billion in 1960s dollars.) This gives us a total cost of about \$10/kg to orbit. This is nearly cheap enough to make ground-launched powersats feasible, but vacations in orbit still cost \$25,000. With a mature nanotechnology, the cost of diamond comes down and the strength goes up. Likewise the high-tech stuff in the track, and power generation, and so forth. (An example: recent progress in micron-scale vacuum tubes suggests that nanoengineering could make high-powered switching apparatus that was more efficient and cheaper than silicon.) Cost reduction on the order of 100 seems feasible. At 10 cents/kg to orbit, the Solar System is our oyster.

Rabbits and Elephants

It certainly seems to be possible with nanotech to reduce the cost of space access, but with a major capital expenditure, which would require a high volume of traffic to amortize. In the early days of flying, there was a saying: Zeppelins breed like elephants, but airplanes breed like rabbits. A realistic guess is that ultimately we will build space piers, but only after the volume of traffic is already such as to make it economically viable.

Your 10-ton Second Atomic Age vehicle is already a car, a boat, and an airplane. How much extra would it take to make it a spaceship?

From the point of view of the passengers, a 1-G thrust would be easy to take; this gets you to orbital velocity in about 13 minutes. You'll travel 3000 kilometers in the process; for each kilometer you will use 100 MJ of energy. If we can get, say, nitrogen fusion to work, 2 fluid ounces of air is all the fuel you need. Otherwise, for the total of 300 GJ, call it fifty cents worth of uranium, if you can get around the rocket equation.

The best way to do that, as long as you're still in the atmosphere, is probably electric jets (ionic thrusters, not RC model fans). They can have high power-to-thrust efficiency, and there's no obvious reason they wouldn't work at hypersonic speeds. [\[273\]](#) No need to try and support

supersonic combustion or put the air through a thermodynamic cycle as in even a simple nuclear-powered ramjet.

All you need is a power source that peaks out at 800 megawatts. Failing that you have to reduce thrust as you get near orbital speed. You are going to have to have a rocket to circularize your orbit anyway.

World Weather Control

The child Alvin was frightened at first. The soaring spires of the city, the moving specks two thousand feet below —these were part of his world, but the thing in the sky was beyond all his experience. It was larger than any of the city's buildings, and its whiteness was so dazzling that it hurt the eye. Though it seemed to be solid, the restless winds were changing its outlines even as he watched.

Once, Alvin knew, the skies of Earth had been filled with strange shapes. Out of space the great ships had come, bearing unknown treasures, to berth at the Port of Diaspar. But that was half a billion years ago; before the beginning of history the Port had been buried by the drifting sand.

Convar's voice was sad when presently he spoke to his son.

"Look at it well, Alvin," he said. "It may be the last the world will ever know. I have only seen one other in all my life, and once they filled the skies of Earth."

They watched in silence, and with them all the thousands in the streets and towers of Diaspar, until the last cloud slowly faded from sight, sucked dry by the hot, parched air of the unending deserts.

—Arthur C. Clarke, *Against the Fall of Night*

Clarke's *Against the Fall of Night*, one of the great classics of Golden Age SF, is set a billion years in the future, when the sun will have expanded to the point of boiling away all the Earth's oceans, leaving only dry, salt-encrusted seabeds on a lifeless planet.

On the other hand, Fritz Leiber's marvelous *A Pail of Air* has the Earth being flipped out of orbit into cold interstellar space by a passing dark star, and all the air freezes into a deep layer of snow.

In Neal Stephenson's recent *SevenEves*, continuing the classic tradition, the moon inexplicably explodes and the rain of the resulting meteors boils and burns the Earth's surface for five thousand years. The same thing had happened to the planet Metaluna in the 1950s SF movie *This Island Earth*.

In the novel and iconic George Pal movie *When Worlds Collide*, a rogue planet actually hits the Earth. Assuming a closing velocity of 30 miles per second (the planet is supposed to have fallen in toward the Sun from interstellar space), the entire Earth would be briefly converted into a 6000° plasma.

Now *that's* global warming.

Anthropogenically-induced climate change today is a favorite hobby-horse of ergophobic activists, Baptists and bootleggers both. It is worth pointing out, yet again, that climate change was *not* the reason for the Henry Adams Curve flatline in the 70s; it didn't get significant traction until the late 80s. Furthermore, like any subject, the horror story bias of the media has served to misinform the general public drastically compared with what scientists and economists actually understand.

It would require much more space than we can spare to address the subject of economic tradeoffs in fossil fuels vs. climate even minimally. Luckily we can simply ignore the issue completely. Second Atomic Age technology could easily power civilization without any CO₂ emissions at all. We should have been building, experimenting, and innovating with it for the past 50 years. Furthermore, to really reclaim our birthright and an optimistic future, we must get back on the Henry Adams Curve. Burning fossil fuels in Earth's atmosphere simply isn't going to support that indefinitely. Burning fossil fuels to explore and develop the Solar System is downright laughable. At what rate we should switch over is a matter of debate, but switch we must.

More to the point, the IPCC predictions that climate change may cost us 3% of a gross world product in 2100 which is 7 times ours today, [\[274\]](#) are made against a conventional economic and technological forecast which might be summarized as “extend the Great Stagnation another 80 years.” Suppose instead we look at what Second Atomic Age technology could actually do over the period, kicking the entire economy onto a Moore's Law curve climbing to 40% growth rates. Our great grandchildren need not be 7 times richer than we are; they could be 20 million times richer than we are. [\[275\]](#) We will be controlling, resculpting, and rebuilding the Earth, and building other Earths, so much and so fast that climate change will be lost in the noise.

Synthesizers

In fact, the major problem in the Second Atomic Age era is most likely to be too little CO_2 in the air rather than too much. Go look at a cornfield: as I write it is still weeks until the Fourth of July, but in these parts the corn isn't just knee-high, it's more than head-high. All of that plant material was created by molecular machines, powered by energy from the sun, out of carbon from the CO_2 in the air. In still air on a clear, sunshiny day, a cornfield depletes all the CO_2 in the ambient air in 5 minutes flat.

Your pocket synthesizer, the Second Atomic Age equivalent of the iPhone, will build you anything — getting the carbon the same way.

Just by way of context, too little CO_2 in the air is a lot more dangerous than too much. Current levels (400 ppm) are much lower than are optimal for green plants; commercial greenhouses operate at 1000 ppm. If we cut CO_2 in half, we would be in serious danger of starving all the green plants of Earth.

So when everyone starts carrying a pocket iPrinter capable of conjuring up anything from snacks to items of clothing out of thin air, we may have to reopen the coal mines and pump out CO_2 just to keep our ecosystem from collapsing.

Air Conditioning

I am but mad North North west; when the wind is Southerly, I knowe a Hauke, from a hand-saw.

—Shakespeare, *Hamlet*



Two 180-mile sunshades. They would be on the order of 100,000 tons of 1-micron aluminized mylar each.

Current efforts to regulate the Earth's climate cost the world economy something on the order of a trillion dollars a year, not counting the externalities of energy poverty and so forth. What's more, by their own criteria, they are not succeeding: global CO_2 emissions are rising faster now than before the Kyoto Protocols were adopted.

Suppose we used the trillion—roughly 50 times NASA's budget— instead to build a robust orbital infrastructure and simply put up some sunshades. The total area needed to negate the enhanced greenhouse effect is seen above, in a 4-satellite configuration where two would always be on the sunside. In practice you would probably use many more much smaller ones. Then not only would you have cooled the climate, you'd have a robust orbital infrastructure, a vastly more valuable thing. For example, if they were solar power satellites instead of merely shades, each one would generate more power than the human race currently uses. More to the point, you would have decoupled the Earth's temperature from the atmosphere's CO_2 content. There is no reason to believe that the optimal levels of the two correspond. With Second Atomic Age technology, it would be essentially trivial to adjust the CO_2 level in the atmosphere to whatever we might want. It is only a rearrangement of atoms.

On the other hand, you might not have to launch your shade into space at all. Construct a small aerostat—a hydrogen balloon—at a guess an optimal size is somewhere on the order of a centimeter in diameter. It has a very thin shell of diamond, maybe just a nanometer thick. It's round, and it has inside it an equatorial plane that is a mirror (possibly extending outside, giving it the shape of the planet Saturn). If you squashed it flat, you would have a disc only a few nanometers thick. Although you could build such a balloon out of materials that we build balloons of now, it would not be economical for our purposes. Given that we can build these aerostats so that the total amount of material in one is actually very, very small, we can inflate them with hydrogen in such a way that they will float at an altitude of twenty miles or so—well into the stratosphere and above the weather and the jet streams.

Each aerostat contains a mirror, and also a control unit consisting of a radio receiver, computer, and GPS receiver. It has just barely enough power and fans or other actuators to tilt itself to a preferred orientation. That's all it does—listens for commands on the radio, and tilts to an angle that is a function of its latitude and longitude. It's not a complicated machine. Now make enough of them to cover the entire globe. For the centimeter size, you'd need about five quintillion. This is why nanotechnology makes a big difference. If you tried to cover the earth with something the total thickness of even a current-day party balloon, let's say about 100 microns, you need on the order of 100 billion tonnes of material, but with the nano-engineered design, just a few nanometers thick, you only need about ten million tonnes. To compare that with the scope of current-day construction, ten million tonnes is roughly the amount of material that is used to make a hundred miles of freeway. This is an amount of material that current-day technology, much less nanotech, can handle straightforwardly.

That is the Weather Machine. We have aerostats which float twenty miles up. They have GPS and controllers and can turn themselves. That's all there is to it. What could you do with a machine like this?

The machine is essentially a programmable greenhouse gas. If you set the mirrors facing the sun, it reflects all the sunlight back. If you set them sideways, it allows the sunlight to come through, and similarly for the longwave radiation coming from the back side of the earth at night. It may help to remember that the amount of energy radiated away by the Earth is

the same, to within tenths of a percent, as the energy coming in from the Sun. We can cool off by shading the Sun. We can warm up by reflecting back our own emitted infrared.

For comparison, the excess radiative forcing associated with human-added CO₂ in the atmosphere is on the order of a watt per square meter. [\[276\]](#) The weather machine would allow direct control of a substantial fraction of the total insolation, on the order of a kilowatt per square meter—1000 times as much. It would completely trump any natural or anthropogenic climatic forcing, and allow us to set Earth's climate to whatever we wanted it to be. For mere overall climate control, we'd only need to build a few tenths of a percent of a full weather machine, enough for just a few watts per square meter. The controls on the individual aerostats can be very simple. When set to let sunlight through, for example, the mirrors can be several degrees away from edge-on to the sun, and the effect would be a scattering of light (visible perhaps as a slight haziness) but no significant reduction in total insolation.

Kardashev Type I civilization

Type	Power	Original definition
I	17	sunlight hitting planet
II	27	total power of sun
III	37	... of galaxy

Kardashev's scale. Power numbers are log watts.

While the *Jetsons* were in their first-season reruns, Russian astronomer Nikolai Kardashev proposed a three-level scale for advanced civilizations. A Kardashev Type I civilization is one that controls all the energy available on a single planet, which is usually estimated as the amount of sunlight hitting it. A Weather Machine would do that—humanity's total current energy (strictly speaking, power) use, at 2×10^{13} watts, is a negligible fraction of the over 10^{17} watts the machine would control.

A Weather Machine could probably double global GDP simply by regional climate control. The economic benefit would be enormous. There is a *huge*

amount of value in being able to control the weather—excuse me, the climate. If you could actually control the climate and tailor it, you could make land in lots of places on the earth, such as Northern Canada and Russia, as valuable as California. Weather control is something that people have always wanted to do; Fifties science fiction is replete with it—not to mention the mythic stories of most major religions! Therefore, once it becomes possible, we probably will.

The better control we have over our aerostats, the more we can do. Controlling insolation on the scale of tens or hundreds of miles would probably give us the ability to affect daily weather patterns as well as climatic averages. A hurricane is a self-organized heat engine running on sea-surface heat. Shade the areas you don't want it to go, and warm a path sending it harmlessly off into mid-ocean.

Given really precise control, you could enhance solar power, for example. Build an array of photovoltaics in the desert and then program about a thousand square kilometers of aerostats above it to focus the sunlight down onto your array. Instead of needing a thousand square kilometers of solar collectors, you need only one. The main reason solar power is expensive is that it's diffuse, so the capital costs for collecting it are high. But with 1000x concentration it should be quite economical. The concentration is more or less free because you have already built the machine to control the weather. What's more, you have not changed the energy balance any, because you are shading all the areas that are otherwise under the thousand square kilometers. That gives your concentrated collector, in broad daylight, an energy flux that is approximately the same as a thousand nuclear reactors of a typical size. Of course, you have to cool the collectors fairly vigorously because they are only about 40% efficient (and that's assuming that current lab results can be turned into commercial usability).

In 2029 the asteroid Apophis is going to make a close approach to the earth, within the orbit of the moon. It will be something of a butterfly effect incident; it is fairly difficult to predict exactly what its orbit will be after that close encounter. Apophis will return in 2036 and we can't say for sure whether it will strike the Earth or not. In 2029, if a highly controllable Weather Machine had been built by then, as the asteroid comes tumbling past we could focus a few petawatts of sunlight on it and give it a kick. (The significant kick would be due to the rocket effect of boiling rock, not light

pressure. But the “butterfly effect” sensitivity at that point is so great that light pressure actually does make a difference.) This is probably a lot more appropriate in the case of Apophis than many other asteroids because it is going to be so close. A small kick in 2029 will have a huge result in 2036, almost certainly enough to prevent a strike, should that actually be the trajectory it is on.

The Weather Machine (Mark II)

The Mark I Weather Machine is something like nanomechanical rod logic—a *gedanken-experiment* existence proof that a given level of technology will have a given capability. We can go farther and talk about what the capability might be like given closer control of light and matter, bearing in mind this is somewhat more speculative.

Take the same aerostat, but inside put an aerogel composed of electronically switchable optical-frequency antennas—these are beginning to be looked at in the labs now under the name of nantennas. We can now tune the aerostat to be an absorber or transmitter of radiation in any desired frequency, in any desired direction (and if we’re really good, with any desired phase). It’s all solid state, with no need to control the aerostat’s physical attitude. Once we have that, the Weather Machine essentially becomes an enormous directional video screen, or with phase control, hologram.

Astronomers hated Weather Machine Mark I, because it acted like a layer of permanent haze in the atmosphere. But they love Mark II because it turns the entire earth into a telescope with an aperture of 8,000 miles. Mark I could zap Apophis as it flew by inside the Moon’s orbit. Mark II is a little more impressive. At the closest approach of Mars, with a transmitting aperture of 10,000 km diameter, using violet light for the beam, you could focus a petawatt beam on a 2.7mm spot on Phobos. A petawatt is about a quarter megaton per second. 2.7mm is about a tenth of an inch. In other words, you could blow Phobos up, write your name on it at about Sharpie handwriting size, or ablate the surface in a controlled way, creating reaction jets and sending it scooting around Mars in curlicues like a bumper car. Mark II, with the ability to shift frequencies and directions independently, is powered at night. Mark I could cool the Earth by shading the sunlight on the dayside, or warm it by reflecting back the infrared that pours into the

night sky. The total power going in and out is very close to the same; incoming power at the surface is roughly a kilowatt per square meter—of surface directly facing the sun, so you only get the full kilowatt at noon near the equator. The whole surface of the Earth is 4 times as large as the sun-facing profile, so the outgoing power is about 250 watts per square meter, but everywhere, all the time. [\[277\]](#) Mark II absorbs the outgoing infrared and uses it. Thus there's plenty of power available for the nightside to do street-lighting, or show ads in the sky, or whatever you'd like. Remember that because it's a hologram, it can have a completely different effect for each spot on the surface: my night sky can be a giant telescope, and my neighbor's can be a giant video game.

Somewhat more usefully, Weather Machine Mark II could simply focus transmitted power to any flying car, not to mention any ship, train, groundcar, or building. For direct conversion to electricity, it should probably be in the microwave atmospheric window at 15 GHz or less (20 mm or more wavelength). You would need less than a one-kilometer patch of Weather Machine to focus on a one-meter rectenna at 15 GHz; that much sky would have 250 megawatts available at midnight.

Spacehounds of IPCC

You control the weather, you control the world!

—Our Man Flint

I'm fairly certain that a Weather Machine, or something like it, will be built sometime this century. It, particularly the Mark I form, seems straightforwardly within the capabilities of molecular manufacturing. There are plenty of people worried about things like climate change or asteroid impact that it could prevent or ameliorate. It could have an enormous economic value. All of these indicate that it should be built, but the most pressing and cogent reason that it actually will be is likely military.

Remember the solar power plant. What if instead of a power plant beneath this thousand square kilometers of concentrated sunlight, there were an army, fleet, or indeed a city? Another way of specifying the amount of energy that would get pumped into the area is that it would be the

equivalent of exploding a one-kiloton bomb every second for as long as you wanted. A Weather Machine would be a very potent weapon, even the Mark I version. Mark II, as noted, could shoot down the moons of Mars.

Even without direct attacks, whoever can control the weather on Earth is pretty much in charge here. Anyone who objects and starts rattling their sabers gets twenty years of no summer and no growing season. (The threat of this, one imagines, will accelerate the trend toward factory farms and synthetics not powered by solar.) For that reason alone, given the technological capability of doing it, it will be done. I cannot see the US government understanding that this is possible and not doing it. In fact, there are several other governments I cannot see understanding it can be done and not doing it.

If you are a smaller government without enough conventional forces to defend yourself well while your Weather Machine is being built, I would guess that approximately 5% of one is all you would need to have a setting that was a dead man switch: if someone came and blew you up and you quit sending out the control signals, all of the aerostats would default into snowball earth mode. It would be a doomsday device. This is troubling. Once somebody gets 5% of one built, you're stuck listening to them. You had better start building your own first, or at least simultaneously. In fact, it seems reasonable to imagine that by later in the century there are going to be several competing clouds of these things around. Hopefully they won't end up physically competing with each other, but that the people in charge of them will come to some negotiation. That's going to be all the more reason for someone wanting to be in the game. You have three quintillion balloons up, and I have one quintillion, and this guy over there has two quintillion, which means we get that many votes in the weather control world government.

The ultimate implications of a Weather Machine are mind-boggling. I can't even come close to seeing all of them, but I'm fairly sure that it's possible and that it will happen. It's worth thinking about.

Here's one simple way to say it: the accidental impact on climate of current (fossil fuel) technology is at least three orders of magnitude smaller than the intentional impact of a mature nanotechnology. If you are Really Worried about the order of magnitude one watt per square meter influence on the Earth of the enhanced greenhouse effect, I urge you to consider in

comparison a Weather Machine which could interdict and/or redirect the full roughly one kilowatt per square meter that's available. Or, to judge by typical diurnal warming and cooling rates, change the global surface temperature at a rate a climate scientist would call 40,000 degrees per decade. Or maybe a shade faster.

Now frankly, this worries me a lot more than natural/accidental climate change. My worry goes as follows: people are so worried about climate that they actually build a Weather Machine. Their models of how climate work are not as good as they think they are; let's say that they are in roughly the same state of actual to perceived knowledge that the Federal Reserve was in macroeconomics in 1929 (or 2008, for that matter). They turn it on and there is, well, a depression. Or multiple governments build them and have wars. Nuclear weapons are trivial by comparison.

Kardashev vs the Flying Saucers

One of the more enduring tropes of science fiction, beginning with Wells' *War of the Worlds*, is the alien invasion. Luckily, it now appears that the solar system is not teeming with intellects vast, cool, and unsympathetic who regard this earth with envious eyes. On the other hand, we have no such guarantee about the rest of the galaxy. We haven't found alien civilizations yet, but among the theories of why we haven't are such hypotheses as that someone came through and wiped them all out, or that they are keeping their heads down against just such a possibility.

If we can make Weather Machine fabric at less than about a gram per square meter, we can put as much of it as we want anywhere in space, not even in orbit, supported against the Sun's gravity by the Sun's radiation. We say "anywhere" because, to a first approximation, the radiation and gravity scale the same way with distance from the Sun.

That means we aren't confined to Weather Machines floating in the skies of Earth; we can put an Earth-sized patch of Weather Machine anywhere.

There's room for about two billion of them at the distance of the Earth from the Sun. If we cover the surface of a sphere around the Sun, we have what's called a Dyson Sphere. Freeman Dyson himself credits the notion to British SF writer Olaf Stapledon; also, before Dyson wrote in 1960, both John

Campbell and E. E. “Doc” Smith had published stories involving the use of the entire output of a star to power a weapon.

If we did build such a gadget—let’s call it a Weather Machine Dyson Sphere or WMDS for short—we could make it of heavier material than the simple light-sail calculation implies. In theory, if the inside were perfectly reflective, you wouldn’t need the continuing sunlight at all; light ricocheting around inside would suffice. It would be a balloon inflated with pure light. In practice, you would have losses which the Sun would make up; the rest of the sunlight would be available as usable power.

Of course surrounding the Sun with a reflector would make it, the Sun, run hot, which might be useful if we decided we needed more power. On the other hand, we would be well advised to make the sphere smaller than Earth’s orbit.

For brief periods, e.g. 10 minutes, we could draw on the “inflating light” inside the WMDS for a higher energy output from the sphere. One obvious case would be if you were shooting at an invading space fleet. Afterwards, however, you would have to wait for the sunlight to reinflate the sphere.

Using a WMDS half the width of Earth’s orbit as a telescope, you could resolve features about 6 inches wide at the distance of Alpha Centauri.

Conversely, you could pour a quarter of the Sun’s power output, *i.e.* 100 trillion terawatts, into a 6-inch spot that far away, [\[278\]](#) making outer space safe for democracy. Just remember that what you see was actually there four years ago, and your beam won’t get there for another four.

——Bottom Line——

These gadgets, particularly the WMDS, seem like big, powerful machines. But it is important to remember just how small the power density of such things would be in Second Atomic Age terms. Given the analyses of projects Orion and Pacer, and the productive capacity of nanotech, however, one can imagine an enormous piston engine where the cylinder explosions are H-bombs. One probably would not couple the piston(s) to a Brobdingnagian crankshaft, however; a free-piston design which generated electric power directly by shoving magnets past coils would be more reasonable. This would be quite a powerful machine. Just one cylinder using 1-megaton charges at one stroke every four minutes would produce 15 terawatts, otherwise known as the total current human energy usage. It could power a Space Pier or Aero City without even noticing the power drain. Replacing each existing powerplant in the US with one makes you a Kardashev Type I civilization at 10^{17} watts, equalling all the sunlight that falls upon the Earth. And this is *First Atomic Age* technology. Your city, or city-sized spaceship, can have several such engines, at a few thousand feet in size, aboard.

Here's another way of defining the Kardashev scale: how much matter does your civilization convert to energy, say in kilograms per second? By a nice coincidence, the number for a Type I civilization is 1 kilogram. The number for type II, which would correspond to the amount the Sun converts, is close enough to ten billion, the ratio between types in the original scale. (There are 100 billion stars in the galaxy, but many of them are red dwarfs, so 10 billion works for the Type II/III ratio as well.)

To put this in perspective, each person in a Type I civilization of 10 billion people would use 10 megawatts, 1000 times the power Americans do now. In a Type II civilization of 10 billion people, each person would use the same energy as an entire Type I civilization. A city-sized spaceship powered by a Pacer Piston is ... your flying car.

24 Rocket to the Renaissance

Let others praise ancient times; I am glad I was born in these.

—Ovid

Still, I persist in wondering whether folly must always be our nemesis.

—Edgar Pangborn

So we near the end of our tour of the future as seen from 1962, and the questions remain: Where is my flying car? When will I get it, if ever? Will we have robots, space travel, ray guns, mechanical educators, weather control, universal libraries, rejuvenation, scientific world government, or limitless atomic power?

The reader is at this time pardoned for expressing a certain impatience. We have paraded before you a smorgasbord of possible technologies, scientific speculations, and Failures of this or that, but have produced no coherent picture of the future. We haven't even shown a complete design for a flying car.

Unfortunately, this is a constraint the futurist has to work within. We can show the limits of the possible, on occasion stepping in Clarkeian fashion just a little past them into the impossible.

The three main phases of technology that drove the Industrial Revolution were first low-pressure steam engines, then machine tools, and then high-pressure engines enabled by the precision that the machine tools made possible. High-pressure steam had the power-to-weight ratios that allowed for engines in vehicles, notably locomotives and steamships. The three major, interacting, and mutually accelerating technologies in the twenty-first century are likely to be nuclear, nanotech (biotech is the “low-pressure steam” of nanotech), and AI, coming together in a synergy I have taken to calling the Second Atomic Age.

Paradigm Shift

There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

— William Thomson, Lord Kelvin (1900)

It is traditional, since Clarke's *Profiles of the Future*, to begin books of futurism like this one with lists of the short-sighted pronouncements of the pundits of the "they said it couldn't be done" type, and then to list the cases where it had in fact been done. The one invariant in futurism before roughly 1980 was that predictions of social change overestimated, and of technological change underestimated, what actually happened. Now this invariant itself has been broken. With the notable exception of information technology, technological change has slowed and social change has mounted its crazy horse and galloped madly off in all directions. H. G. Wells' image of the feckless Eloi, a lampoon of the effete idle English upper classes of a century ago, describes us better than he could have imagined. The question of flying cars has long been one flung back at technological futurists. Around the turn of the century some of the researchers in the NASA Ames nanotech effort asked me to look at what the capabilities of mature nanotech could do to build flying cars. I found the technical problems interesting but not difficult. Becoming a pilot and airplane owner in the meantime has changed my appreciation of some of the details, but not the main conclusion. Nanotech could give us personal spaceships; flying cars are essentially trivial by comparison. But there the question rested for some time. There now appears to be some renewed interest in "What happened to the future we were promised?" partly due to the 50th anniversary of the Space Age. But the general take still seems to be that flying cars, and all the other hoped-for technologies, were over-promised. On closer inspection, this gets it almost completely backwards. Flying cars of the convertible type are technologically straightforward. Not only are they easily within reach of the capabilities of today, but they have been built, and successfully flown, with almost monotonous regularity by individuals and small companies since the 1930s. The autogyro had both the innovative brilliance that would have allowed short home runways and a dedicated, experienced, and well-funded sponsor.

Unfortunately, in the 1930s, marketing a new, non-mass-produced vehicle into Depression America was not a winning proposition.

In the 1940s, WWII sucked virtually all our engineering talent into war production. The size of the aviation industry quadrupled. The average American was just as unable to afford a car as in the depths of the Great Depression. In the postwar Forties, several quite workable convertible airplanes were developed.

In the 1950s, delays associated with aircraft regulation blunted the supply side of flying cars and the burgeoning investment in superhighways, bridges, and other infrastructure blunted the demand side. The government spent an inexplicable amount of time and resources trying to prevent Pitcairn from getting his due, incidentally preventing him from spending his time, energy, and resources on developing personal flying machines in the postwar era. Even so, a handful of convertible flying car types got aircraft certification and came close to production, in a world where real disposable income was a third of today's. Helicopters developed into a practical form of transport but remained too expensive for the average family.

In the 1960s, passenger jet travel came into its own, becoming a major new mode of transportation. Alongside that, the 60s were a heyday of private aviation; a reasonable extrapolation of the trend would have put a fair number of us in flying cars today. In the 60s, perfectly workable if noisy car-sized VTOLs, e.g. the AirGeeps, were developed by the military.

In the 1970s, the centuries-long growth trend in energy (the "Henry Adams curve") flatlined. Most of the techno-predictions from 50s and 60s SF had assumed, at least implicitly, that it would continue. The failed predictions strongly correlate to dependence on plentiful energy. American investment and innovation in transportation languished; no new developments of comparable impact have succeeded highways and airliners.

Also in the 70s, academia became a major locus of counter-cultural fervor, as it morphed into a largely virtue-signalling institution driven by competitive self-deception. This set up a classic Baptists-and-Bootleggers bedfellowship between those who really believed that progressive prescriptions would improve the world, and those who mostly enjoyed the new money, prestige, and policy-making influence. Public spending, and PhDs granted, tripled from 1960 to 1980. The war on cars was handed off from beatniks to bureaucrats in the 70s. Supersonic flight was banned.

Bridge building had peaked in the 1960s, and traffic congestion now is 5 times as bad as then.

Around 1980, developments in liability law destroyed the private aviation industry. Regulation exploded; a significant proportion of decisions in business went from being made by people who were forced to balance costs with benefits to being made by bureaucrats with no concern for costs. Increasingly in our economy, the cost disease replaced the learning curve. The nuclear industry found its costs jacked up by an order of magnitude and was essentially frozen in place. Interest and research in nuclear physics languished.

Over the period of interest, Green fundamentalism has become the unofficial state church of the US (and to an even greater extent Western Europe). Its catechism is a litany of apocalyptic prophecies, each forgotten in detail as it failed, but adding in vague spirit to an overall angst of original sin and impending doom. This has contributed in no small part to the neurotic pessimism of our current culture, by objective measures the richest, safest, and healthiest in history.

In technological terms, bottom line is simple: we could very easily have flying cars today. Indeed we could have had them in 1950, but for the Depression and WWII. The proximate reason we don't have them now is the Henry Adams curve flatline; the reasons for the flatline have taken a whole book to explore. We have let complacent nay-sayers metamorphose from pundits uttering "It can't be done" predictions a century ago, into bureaucrats uttering "It won't be done" prescriptions today.

The Future We were Promised

Then answered Amos, and said to Amaziah, I was no prophet, neither was I a prophet's son; but I was an herdsman, and a gatherer of sycamore fruit.

—Amos 7:14

Normally in history, technology has led science. Tinkerers find things that work, and scientists come along and explain them, in the process laying the groundwork for more thorough exploitation of the principles involved. People had been burning wicks in oil and tallow-wax for millennia before Faraday's famous lectures on the candle flame. The makers of wine and cheese had likewise been using microbes long before Pasteur identified them. Steam engines had been in use for a century before Carnot elucidated the principles of thermodynamics.

Yes, we should have flying cars. Yes, we should have power too cheap to meter. Yes, we should have orbital hotels and a base on the moon. Average family income in the US should be \$200k by now, and growing at a sustained 6%. But what has actually happened is that cultural reaction and regulatory ossification have combined to dam up the normal flow of experimentation in high power technology. Where the technium would have spilled into the fertile valleys in idea space, we have instead built up a theoretical, scientific overhang. We built and tested molten salt reactors and nuclear rocket engines over 40 years ago, but in the interim the United States has effectively used experimentation with nuclear capability as a *casus belli* against anyone who has tried it. We could have been developing nanotech since 1960 when Feynman first pointed out the possibilities. We know a lot more about the molecular scale now, so when the dam breaks it will come a lot faster. We have system designs for self-replicating nanofactories. We have detailed, atom-for-atom designs and engineering analyses of gears, levers, bearings, shafts, and sprockets. We can simulate the quantum electrodynamics on our almost ridiculously powerful

computers now. It is as if we had gone into the Industrial Revolution already knowing thermodynamics and high-temperature metallurgy. Should the cultural pendulum swing back, should we lose our idiotic fear of energy and regain the Henry Adams curve, or should there arise elsewhere a culture that has the same innovative spirit that we had just a century ago, huge technological advances could happen almost overnight as experimentation regains the lead, using all the “pent-up knowledge” of the past half-century as the overhang collapses, the dam breaks, and the technium surges into the forbidden valleys.

It could even happen here, though that is by no means a foregone conclusion. *Pax Americana* has lasted seven decades but there are signs that the end may be in sight. Under its umbrella the forces of cultural variation have reigned supreme, but selection has fallen fallow. It is all too easy to assume that any recent direction of cultural evolution is the unalterable wave of the future; but the Gods of the Copybook Headings are not to be held at bay indefinitely by ignoring them. The “same boat” spirit that empowered the postwar industrial state up through the Cold War is gone with the wind. Technologies that provoke antipathy and promote discord, such as social networks, are the order of the day; technologies that empower everyone but require a background of mutual trust and cooperation, such as flying cars, are considered amusing anachronisms.

Nuclear power and nanotech are the most obvious examples of overhang technology; many others can be found by filling in the top right half of the expected-vs-achieved technologies chart. You will recall that the technologies not achieved had a strong bias toward high energy intensity. Space travel is a prominent thread among them. High-power technologies promote an active frontier, be it the oceans or outer space. Frontiers in turn suppress self-deception and virtue signalling in the major institutions of society, with its resultant cost disease. We have been caught to some extent in a self-reinforcing trap, as the lack of frontiers foster those pathologies, which limit what our society can do, including exploring frontiers. But by the same token we should also get positive feedback by going in in the opposite direction, opening new frontiers and pitting our efforts against nature and not each other.

Breakthroughs in the overhang technologies would allow the rest of the world to catch up with the stagnating Western civilization in a rerun of the

collapse of *Pax Britannica*. Weapons also have a strong high-power bias. Nanotech would enable cheap home isotopic separation. Short of that, it would enable the productivity of the entire US military-industrial complex in an area the size of, say, Singapore. It's available to anyone who has the sense to follow Feynman's pathway and work in productive machinery instead of ivory-tower tiddley-winks. The amount of capital needed for a decent start is probably similar to a well-equipped dentist's office. Cold fusion, H-B11 fusion/fission, or any other nuclear power breakthrough enabling vehicle-sized reactors or nuclear-density batteries, would have a similar effect.

AI, not an overhang technology but one that seems very much on the predicted track, turns production of machines into production of robots. This obviates the advantage of a large developed nation from either a population of soldiers or a cadre of educated engineers. If a mature nanotech can build an America's worth of capital equipment in a week, adding AI to that gives you an America's worth of untiring, unsleeping, reliable, competent, honest, trustworthy workers.

Navigation

The rapid Progress true Science now makes, occasions my Regretting sometimes that I was born so soon. It is impossible to imagine the Height to which may be carried in a 1000 Years the Power of Man over Matter. We may perhaps learn to deprive large Masses of their Gravity & give them absolute Levity, for the sake of easy Transport. Agriculture may diminish its Labour & double its Produce. All Diseases may by sure means be prevented or cured, not excepting even that of Old Age, and our Lives lengthened at pleasure even beyond the antediluvian Standard. O that moral Science were in as fair a Way of Improvement, that Men would cease to be Wolves to one another, and the human Beings would at length learn what they now improperly call Humanity.

—Benjamin Franklin (1780)

The science fiction of the Forties and Fifties was written in a world of burgeoning aerospace capabilities and reflected that in its visions of the future. Similarly, they assumed the future would be powered by nuclear energy, or more precisely by engines that would stand in the same relation to the “atomic piles” of the day that gas turbines do to medieval black-powder cannon.

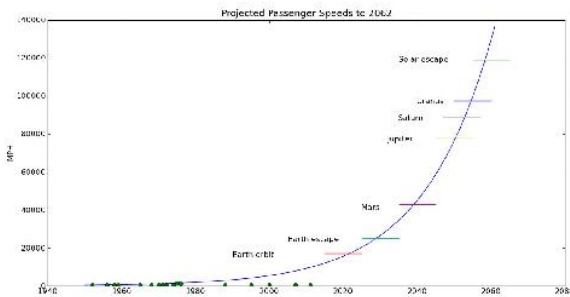
The future isn’t what it used to be. The hot technologies of today are computing, communication, and biotechnology. Modern SF (and futurism) has a tendency to predict a future along just as simple a linear extrapolation as did *The Jetsons* in its day. But it would be a major Failure of Nerve, much less of Imagination, to assume that the course of technology has ceased to change. Most of the technologies I’ve examined here are those we could have had by now but dropped the ball; that was to be expected, given the focus of the book.

Second Atomic Age technology is not something beyond our grasp. It is something we have been too busy “being Wolves to each other” to get to work and build. But let us imagine that by some miracle we managed to find Benjamin Franklin’s “moral Science,” perhaps something like cybernetics as originally envisioned, get back on the Henry Adams curve, and regain our legacy as a productive, growing, improving and optimistic culture.

This is neither impossible nor a mere pipe dream. Necessity is the mother of invention; I have, as a technologist, tended to concentrate on the invention side of the equation in this book. But the necessity side, the gap between how well off we are and how much better we would be with the solution to some problem, is the pull to invention’s push. The quality of governance is probably the strongest case in point: The whole world could be at Rosling’s Level 4 now, but is spread out in a slightly down-skewed distribution from 4 to 1. At a weighted average, the world could be 16 times as wealthy as it is now, if only our political systems were honest and competent. 15 times the world’s output is an enormous value, simply sitting there waiting to be reaped. As a futurist, I will go out on a limb and make this prediction: when someone invents a method of turning a Nicaragua into a Norway, extracting only a 1% profit from the improvement, they will become rich beyond the dreams of avarice and the world will become a much better, happier, place. Wise incorruptible robots may have something to do with it.

Turning a Level 4 world into a Level 5 world, with flying cars, is worth very roughly another 50 times the current total output of the human race. That's a fair incentive.

Tripularity



Second Atomic Age technology is more or less implied by the passenger speeds trend curve by mid-century.

The three core technologies that form what I have termed the Second Atomic Age are

- Substantial control of the structure of matter at the atomic (and any larger) scale
- The ability to tap in a controlled way into the vast ocean of power revealed by the nuclear curve of binding energy
- The know-how to build competent, intelligent information processing and decision-making systems

The difference between such a technology and that of today, in all three areas, is probably similar to the difference in technology in the US during WWII as compared to the Revolutionary War. We have suppressed or dropped the ball on some of these over the past half-century, but it seems perfectly possible, technologically, to regain the pace and have a *Jetsons'* world by 2062—if we want to.

Let's look at the technology list again, and see where we might be by 2062 if we can manage to do things more-or-less right:

- Artificial Intelligence. Not an overhang technology per se, but one which is advancing about as fast as anyone could reasonably expect. AI seems to have come to an accelerating takeoff point: major development has shifted out of universities and into industry, with the concomitant resources and feedback from the increase of capabilities. Expect exponential growth over the next couple of decades: your model is aviation just a century ago. We will almost certainly have human-level intelligence by 2062; in fact, we will probably have average-human level AI by 2030. The problem with predicting superintelligence is that we don't actually know what it is; but the equivalent of "Google in a box" is reasonably likely by the latter half of the century.
- Nanotech. A fully-capable atomically-precise manufacturing base technology in turn enables physical productivity growth at Moore's Law rates. The atomic bomb gave us the capability to fly a single airplane over a city and destroy it in the span of a few short minutes. Nanotech gives us the ability to build a brand new city on the same timescale. We could have had it beginning roughly now; we could certainly have it by 2062.
- Biotech. We appear to be exactly on the cusp of the overhang collapse in this area. In just the past few years, a technique known as CRISPR [\[279\]](#) has given biotechnologists a powerful, high-precision editing tool for genomes. Pent-up biological knowledge can now be used for everything from cancer prevention to ecosystem modification. Our Lives may be lengthened beyond the antediluvian Standard. Expect Astro the talking dog before 2062. Expect to live long enough to see him.
- Nuclear power. If not for the stagnation of nuclear physics, this would be an enormous overhang; it remains a substantial one. We clearly know enough to advance a couple of generations in power reactors in one jump. There are several interesting approaches to small fusion reactors being looked at with various degrees of support, as well; some of them may come to something.
- Cold fusion. Whether this turns into a usable energy source remains a toss-up. On the other hand, interest and experimentation in the field has grown substantially over the past decade. It is likely a Failure of

the Imagination to contend that no controllable, compact mechanism for tapping the truly gigantic reservoir of energy available will be discovered in the coming century.

- The end of the age of heat engines. There are different ways this could happen, so the result is more likely than any of the particular pathways. Fuel cells are getting close to being usable now; nanoengines could convert chemical potential energy directly into mechanical force, or voltage, without thermalizing it. The same phenomenon is available to biotech: the Krebs cycle in mitochondria is exactly such a non-heat-engine fuel cell. Stimulated radioactive decay or aneutronic fusion could produce energetic charged particles that could be tapped directly for voltage.
- The end of the age of fuel. This depends on at least one of the nuclear-derived power sources working out, but again there are multiple possible pathways, and transmitted power may contribute. Within a couple of decades, no gadget, from cellphone to lawnmower, will need recharging or refueling; it will come with enough energy built in to last the life of the mechanism. Your ground car and your home's power unit will be refueled upon annual maintenance. Higher-power mechanisms, such as VTOL flying cars, airliners, and spaceships might need to refuel more often, though.
- The end of (solar powered, dirt based) agriculture. There will probably be a full cycle of factory food production, which is in its turn replaced by direct nanotech food synthesis.
- Flying cars. Advances in aerodynamics, particularly computer simulation, have mostly been put to the purpose of squeezing the last ounce of efficiency out of existing flying vehicle types. Regulation has vitiated experimental research into car-sized machines. However, the explosion of interest and research—and results—in models and drones is beginning to look like overhang collapse. Today, about 20 companies appear to be trying to develop flying cars, all along the spectrum from VTOL to convertible airplane types to modularity. [\[280\]](#) Many of these appear to be serious, reasonably well-funded efforts with at least some chance of getting through the regulatory hurdles and into the marketplace. By 2062, robotic flying cars at least as fast as today's airliners could be commonplace. The end of agriculture means

that vast areas ideally suited to flying cars might open up for habitation.

- Sea cities, domed cities, Aero City: Energy is the major enabler, with nanotech for the cloud cities. Cities with “moving ways,” multi-level streets, and and so forth are much more likely to be economically feasible with a nanotech industrial base. We could put the population of the US into mile-high towers 20 miles apart, and leave the rest untouched; alternatively, we could have 50-story *Jetsons*-like apartment buildings about 2 miles apart. But we could also put a large fraction of people into widely-scattered but easily-accessible country estates.
- There will almost certainly be a growing trend to improvement, not just repair/restoral, of the basic human body, to the extent for example that we could comfortably live in space, or under the sea, indefinitely. It remains to be seen whether we prefer to adapt ourselves to Earth’s less clement climes or change them to suit us. Fill the Pacific with new tropical islands, or equip ourselves with gills?
- Space travel. Either compact power or nanotech would put lunar, orbital, and Mars colonies within reach. Both together would open the floodgates to the solar system. This will be nowhere near complete by 2062, but could be getting under way.
- Cybernetics. The overhang here—the gap between how well our social systems might work with the knowledge we have, and how well they actually do—is immense. We have many, many systems that desperately need feedback built in. There seems to be a hint of movement, at least in science; you see more and more stories about how replication, which is supposed to be the feedback mechanism, is failing, and there are various efforts afoot to fix that. More and more of society’s rust-encrusted corruption-choked mechanisms are being attacked by infotech-based entrepreneurs, such as Bitcoin and Uber. We shall see.

Here is the choice that’s facing us in the coming century: will we as a society pick a comfortable, static level of existence, requiring a modest amount of production which volunteers and robots could easily supply? (You get roughly the same scenario of 98% unemployment using 1962

consumption levels and 2062 projected productivity, as we did in our *gedankenexperiment* of the 1790 consumption levels and current technology.) Humans could essentially retire, but they will then spend a vast amount of energy on makework, self-deception, and being Wolves to each other.

This is not merely a guess. One of the really towering intellectual achievements of the 20th Century, ranking with relativity, quantum mechanics, the molecular biology of life, and computing and information theory, was understanding the origins of morality in evolutionary game theory. The details are worth many books in themselves, but the salient point for our purposes is that the evolutionary pressures to what we consider moral behavior arise *only in non-zero-sum interactions*. In a dynamic, growing society, people can interact cooperatively and both come out ahead. In a static no-growth society, pressures toward morality and cooperation vanish; you can only improve your situation by taking from someone else. The zero-sum society is a recipe for evil.

The opposite vision is of a dynamic society. Increased productivity, instead of allowing fewer people to produce the same fixed output, can allow everyone to do more and more. This is a world of makers instead of takers. This is the world in which everyone can afford a million-dollar flying car and buy tickets on spaceships. This is the world where we build cities on the sea and colonies in space. This is the world in which humanity is able to preserve the Earth as a park and take our fights outdoors.

The society we live in today is a vast hodgepodge and double exposure of the two visions. The open, dynamic world of computers and electronics has given us many of the predicted wonders of classic science fiction: the pocket telephone; the computer itself as both personal appliance and as vast supercomputers that (kind of) predict the weather; the world library instantly available in your home; giant wall-screen television that can be used as a videophone. The closed world of regulation (or full-fledged government control) has dragged personal airplanes, space flight, atomic power, and the like down to rot on the ground, and infected education, medicine, transportation infrastructure, and so forth with the cancer of cost disease. Other sectors of progress lie in between. The slide in that direction essentially defines the Great Stagnation; it's why you don't have a flying car.

Being Tom Swift

Man has mounted science, and is now run away with. I firmly believe that before many centuries more, science will be the master of men. The engines he will have invented will be beyond his strength to control. Someday science may have the existence of mankind in its power, and the human race commit suicide, by blowing up the world. Not only shall we be able to cruise in space, but I'll be hanged if I see any reason why some future generation shouldn't walk off like a beetle with the world on its back, or give it another rotary motion so that every zone should receive in turn its due portion of heat and light.

—Henry Adams (1862)

My experience of men has neither disposed me to think worse of them, or indisposed me to serve them; nor, in spite of failures which I lament, of errors which I now see and acknowledge, or of the present aspect of affairs, do I despair of the future.

The truth is this: The march of Providence is so slow and our desires so impatient; the work of progress is so immense and our means of aiding it so feeble; the life of humanity is so long, and that of the individual so brief, that we often see only the ebb of the advancing wave and are thus discouraged. It is history that teaches us to hope.

—Robert E. Lee (1870)

For ... he could see that the new American—the child of incalculable coal-power, chemical power, electric power, and radiating energy, as well as of new forces yet undetermined—must be a sort of God compared with any former creation of nature. At the rate of progress since 1800, every American who lived into the year 2000 would know how to control unlimited power. He would think in complexities unimaginable to an earlier mind. He would deal with problems altogether beyond the range of earlier society. To him the nineteenth century would stand on the same plane with the fourth—equally

childlike—and he would only wonder how both of them, knowing so little, and so weak in force, should have done so much.

—Henry Adams (1907)

As we slid from an optimistic world toward a pessimistic one, science fiction reflected the shift. From the technocratic utopia of *Things to Come*, to the future-as-now-but-improved background of *Forbidden Planet*, *The Jetsons*, and *Star Trek*, to the dystopias of modern SF in the vein of *Terminator* and *Blade Runner*, SF tracked our loss of faith in the future. Jill Lepore, Harvard historian, in a review of the rise of the dystopian in science fiction, says,

Dystopia used to be a fiction of resistance; it's become a fiction of submission, the fiction of an untrusting, lonely, and sullen twenty-first century, the fiction of fake news and infowars, the fiction of helplessness and hopelessness. It cannot imagine a better future, and it doesn't ask anyone to bother to make one. It nurses grievances and indulges resentments; it doesn't call for courage; it finds that cowardice suffices. Its only admonition is: Despair more.

Perhaps Ray Bradbury captures it most poetically in *The Toybee Convector*:

I was raised in a time, in the sixties, seventies, and eighties, when people had stopped believing in themselves. I saw that disbelief, the reason that no longer gave itself reasons to survive, and was moved, depressed and angered by it. ... Everywhere was professional despair, intellectual ennui, political cynicism. ... The impossibility of change was the vogue. ... Bombarded by dark chaff and no bright seed, what sort of harvest was there for man in the latter part of the incredible twentieth century? Forgotten was the moon, forgotten the red landscapes of Mars, the great eye of Jupiter, the stunning rings of Saturn.

Isaac Asimov once said, "The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom." This was to a great

extent an echo of Benjamin Franklin's "moral Science" sentiment. Perhaps the most salient misprediction of Golden Age SF was that it largely assumed that society would remain wise enough to allow technology to continue improving life. Asimov stoutly maintained in his writings and talks that it was only science and technology that had ever improved human life, and that putting one's faith in politicians, priests, and crusaders was a fool's errand. He was surely right.

Mid-century SF was hardly lacking dystopias or pessimism, with the iconic *1984* followed by a whole sub-genre of nuclear war apocalypse. Pessimism has always sold, and been intellectually fashionable. John Stuart Mill had observed it a century before that, writing "Not the man who hopes when others despair, but the man who despairs when others hope, is admired by a large class of persons as a sage." Thomas Babbington Macaulay, the great historian of England, had written in 1830,

On what principle is it that, when we see nothing but betterment behind us, we are to expect nothing but deterioration before us? If we were to prophesy that in the year 1930 a population of fifty million, better fed, clad, and lodged than the English of our time, will cover these islands, that Sussex and Huntingdonshire will be wealthier than the wealthiest parts of the West Riding of Yorkshire now are, that machines constructed on principles yet undiscovered will be in every house, many people would think us insane.

And of course Macaulay was exactly right, and the doomsayers spectacularly wrong. This was the Victorian era, the Industrial Revolution, the greatest sustained improvement of human conditions in history. Science fiction has a long and valuable history of providing us with visions of a better world. Verne, Wells, Burroughs, Gernsback—even Bellamy—much less Campbell, Doc Smith, van Vogt, Heinlein, Asimov, Garrett, Piper, Niven, and Pournelle, provided people with places and lives they could imagine and aspire to create. Science fiction since the Sixties has signally failed in that regard; we have been fed, by and large, a diet of Chicken Little soup in a pot of message, ladled out over leg of Frankenstein. The future turned out to be a massive orgy of meaningless social masturbation. By this Faustian bargain, SF gained academic

respectability and climbed out of its literary ghetto. It became a literature not of technological and scientific ideas, of adventure and hope, but of ivory tower snobbery, looking down on ordinary people and their aspirations for flying cars and a better future. Decadent ergophobia is ever so much more stylish and avant-garde. Can SF regain its soul and we the future we were promised?

The two Henry Adams quotes above reflect two different takes on the possibilities of technology, filtered through the zeitgeist of different times. But in Adams' case they had shifted from a pessimistic view during the Civil War to an optimistic one in the halcyon days of the height of Civilization in the Edwardian decade. Twilight falls but daybreak follows. The Great Stagnation was the Qing Dynasty self-strangulation rerun at internet speed. The internet itself is the printing press of the information age; remember that the printing press was responsible not only for the rise of science but for centuries of religious wars as people escaped the yoke of the centralized information control of the medieval Church. Remember that the medieval Papacy was just as venal, grasping, entrenched, and held sacred and infallible by a large segment of the people as is our monstrous bureaucracy today. And yet the Reformation happened. It is history that teaches us to hope.

We have skirted around the edges of a technology which would be as far beyond our current machines in power, in range, and in productive capacity as Industrial Revolution technology was beyond subsistence farming with hand tools. In many ways the Second Atomic Age could far exceed what science fiction writers, much less "respectable" futurists, predicted. They knew we could build crystal cities high above the scorched plains of Texas; few of them realized that we might convert those plains into a Big Sur or Yosemite at will. They knew we could have flying cars; few realized we might remake ourselves so that we might fly unassisted. They knew we could walk on other worlds; few realized we could build other worlds, or live at ease and in comfort in space itself.

Tom Swift, Jr. had a Flying Lab—a huge airplane able to go anywhere in the world, packed with every kind of equipment, from chemistry glassware to machine tools, that a boy genius could want. It even carried a small helicopter to buzz around in after you landed somewhere. How many things could you discover or invent if you had something like this?

You do have something like this now, in the virtual world: you can “go” all over the world on the Internet, talk to any of a vast number of people if you wish. You have access to more computing power and design and simulation software than existed in the entire world in 1962. You can experiment, you can tinker, you can invent, you can build.

The Second Atomic Age story shows us that this can happen in world of atoms as well as the one of bits. A real flying lab, if you want, but at any rate a lab, a machine shop, a 3-D printer capable of making more things than you can imagine, and in particular capable of making something that only you have imagined that can improve the world. Your lab is not just full of machines but staffed by intelligent robots expert in the full history of science and engineering.

If we did get back on the Henry Adams Curve, with energy and population growth in their historic proportions, by 2200 or so we would reach the status of a Kardashev Type I civilization, with about 30 times the population and 30 times the power per capita as today. This would be a disaster if they all lived on the Earth’s surface, but would be just about right for a broadly-based solar-system-scale civilization. The resumption of a dynamic ethic in an open frontier could serve to reduce the primacy of virtue signalling and cost disease in our major institutions.

It is a possibility. The key to that future will be our visions: whether we can imagine, want, and try hard enough to achieve great things—things worthy of the capabilities of a people with intelligent robots, complete control of the structure of matter, and the limitless power of the atom. Our muscle awaits if only we can find our muse. We need hoppers and dreamers, we need visionaries who can see a better future worth striving for. We need great, *important* things to do with the staggeringly huge capabilities that lie within our grasp. Science fiction must get back down into the gutter and start looking back up at the stars.

As for the future, your task is not to foresee it, but to enable it.

—Antoine de Saint-Exupery

It is not really necessary to look too far into the future; we see enough already to be certain it will be magnificent. Only let us hurry and open

the roads.

—Wilbur Wright

*Come, my friends,
'Tis not too late to seek a newer world.
Push off, and sitting well in order smite
The sounding furrows; for my purpose holds
To sail beyond the sunset, and the baths
Of all the western stars, until I die.
It may be that the gulfs will wash us down:
It may be we shall touch the Happy Isles,
And see the great Achilles, whom we knew.
Tho' much is taken, much abides; and tho'
We are not now that strength which in old days
Moved earth and heaven, that which we are, we are;
One equal temper of heroic hearts,
Made weak by time and fate, but strong in will
To strive, to seek, to find, and not to yield.*

—Tennyson, *Ulysses*

Appendix A: Airliner Speeds

Most figures from Wikipedia pages for the specific airliners. Speeds are standard service cruising speed if given, or calculated as 90% of aircraft maximum speed otherwise. Dates are of service introduction.

Introduction	Cruising speed mph	Airliner
1910	44	Wright Model B
1913	55	Sikorsky Ilya Muromets
1919	75	Farman F.60 Goliath
1926	90	Ford Trimotor
1934	189	Douglas DC-2
1936	207	Douglas DC-3
1942	227	Douglas DC-4
1945	340	Lockheed Constellation
1947	311	Douglas DC-6
1947	301	Boeing 377
1948	316	Vickers Viscount
1952	460	De Havilland Comet
1956	531	Tupolev Tu-104
1958	607	Boeing 707

1959	593	Douglas DC-8
1965	558	McDonnell Douglas DC-9
1968	485	Boeing 737
1970	555	Boeing 747
1971	564	McDonnell Douglas DC-10
1972	530	Tupolev Tu-154
1974	518	Airbus A300
1975	1420	Tupolev Tu-144
1976	1340	Concorde
1988	511	Airbus A320
1995	560	Boeing 777
2000	570	Boeing 747-400ER
2007	528	Airbus A380
2011	567	Boeing 787

Date	Speed	Aircraft
1975	1420	Tupolev Tu-144
1976	1340	Concorde

1988	511	Airbus A320
1995	560	Boeing 777
2000	570	Boeing 747-400ER
2007	528	Airbus A380
2011	567	Boeing 787

Small (6 seater) private turboprops and jets. Price in millions. Speed is max cruise in knots; one can typically reduce speed by 10 percent and increase range by roughly the same fraction. Payload is in pounds when completely filled with fuel; a small jet typically holds over 2500 pounds of fuel, so range can be traded off for payload. Range is in nautical miles. Except as noted, turboprops are single-engine; jets are twin-engine. Jets typically require twice as long a runway as turboprops.

Airplane	\$M	speed	payload	range	type
Epic E1000*	2.9	325	1120	1650	tp
Embraer Phenom 100E	4.2	390	602	1178	jet
Eclipse 550	2.9	375	703	1125	jet
Pilatus PC-12	4.6	280	1009	1309	tp
Piper PA-46 Meridian	2.2	260	358	1000	tp
Daher TBM 900	3.7	330	720	1585	tp
Beech King Air C90GT	3.8	272	358	1289	twin tp
Cessna Citation 510	3.2	340	600	1200	jet

HondaJet	4.5	420	600?	1180	jet
Cirrus SF50*	2	300	1200	560	jet**

* Currently in the certification process.

**Single engine jet. Single engine jets are surprisingly rare, given that there are plenty of single engine piston planes and jet engines are both more reliable and much more expensive than pistons. The reasons appear to be originally regulatory, and the regulations have been the environment for so long that the culture will have a hard time taking advantage of any change.

Appendix B: Bibliography

Sources for background and further reading. I have tried to include much of what I consider “classic” science fiction, i.e. which would have contributed to the overall sense of “the future we were promised.” In many cases with non-fiction I have included books that are readable rather than more voluminous academic tomes (e.g. Toynbee’s *Civilization on Trial* rather than his *Study of History*). Except for the FAR/AIM, you might reasonably expect to read or to have read all of these. This does not include scientific papers, which are referenced in footnotes. If you want to go deeper into any of these subjects, the books themselves, not to mention Google, will be your guide.

The World of Tomorrow

Victor Appleton II: Tom Swift and his Triphibian Atomicar

Hugo Gernsback: Ralph 124C 41+

Arthur C. Clarke: Profiles of the Future

H. G. Wells: Things to Come

Isaac Asimov: Nine Tomorrows

Robert A. Heinlein: Podkayne of Mars

Kahn & Wiener: The Year 2000

Gregory Benford: The Wonderful Future that Never Was

Corn & Horrigan: Yesterday’s Tomorrows

Oona Strathern: A Brief History of the Future

David Gelernter: 1939: The Lost World of the Fair

The Conquest of the Air

Jules Verne: Robur the Conqueror

Juan de la Cierva: Wings of Tomorrow: The Story of the Autogyro

Frank Kingston Smith: Legacy of Wings: The Harold F. Pitcairn Story

Patrick Gyger: Flying Cars: The Extraordinary History of Cars
Designed for Tomorrow's World

Andrew Glass: Flying Cars: The True Story

George Green: Flying Cars, Amphibious Vehicles and Other Dual
Mode Transports: An Illustrated Worldwide History

The Graveyard of Dreams

Tyler Cowen: The Great Stagnation

Robert Prehoda: Designing the Future

Philip Francis Nowlan: Armageddon: 2419 A.D.

Robert Cartmill: The Next Hundred Years... Then and Now

Geoffrey Hoyle: 2011: living in the future

Mancur Olsen: The Rise and Decline of Nations

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Waldo and Magic, Inc.

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K. Eric Drexler: Engines of Creation; Nanosystems

J Storrs Hall: Nanofuture

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Edgar Rice Burroughs: The Gods of Mars

David Freedman: Wrong

Kevin Kelly: What Technology Wants

Bryan Caplan: The Case Against Education

Steven Johnson: Where Good Ideas Come From

Matt Ridley: The Evolution of Everything: How New Ideas Emerge

Terrence Kealy: The Economic Laws of Scientific Research

Cold Fusion?

John Huizenga: Cold Fusion, the Scientific Fiasco of the Century

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Alex Tabarrok: Launching the Innovation Renaissance

Austin B Hallock: Sky Full of Dreams

Philip Howard: The Death of Common Sense

FAA: Federal Aviation Regulations / Aeronautical Information Manual

The Age of Aquarius

H. G. Wells: The Time Machine

Robert Trivers: Deceit and Self-Deception: Fooling Yourself the Better to Fool Others

Kevin Simler & Robin Hanson: The Elephant in the Brain: Hidden Motives in Everyday Life

Rachel Carson: Silent Spring

Meiners, Desrochers, & Morriss: Silent Spring at 50: the False Crises of Rachel Carson

The Club of Rome: Limits to Growth

Jerry Pournelle: A Step Farther Out

Julian Simon: The Ultimate Resource

Matt Ridley: The Rational Optimist

A Car in Every Garage

Arthur C. Clarke: Childhood's End

E. E. "Doc" Smith: Skylark Three

H. G. Wells: Men Like Gods; Anticipations

Edward Bellamy: Looking Backward

Trevor Williams: A Short History of Twentieth Century Technology

D. S. L. Cardwell: Turning Points in Western Technology

Hans Rosling: Factfulness: Ten Reasons We're Wrong About the World—and Why Things are Better Than You Think

Ceiling and Visibility Unlimited

Orville & Wilbur Wright: The Early History of the Airplane

John Denker: See How It Flies

H. G. Wells: The War in the Air

James Tobin: To Conquer the Air

Antoine de Saint-Exupery: Wind, Sand, and Stars

Ernest K. Gann: Fate is the Hunter

Richard Bach: Jonathon Livingston Seagull

Dialogue Concerning the Two Great Systems of the World

Steve Markham & Bill Holder: Straight Up: a History of Vertical Flight

James R Chiles: The God Machine: From Boomerangs to Black Hawks: The Story of the Helicopter

Bruce Charnov: From Autogiro to Gyroplane: The Amazing Survival of an Aviation Technology

The Atomic Age

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L. Sprague de Camp: Man and Power: the Story of Power from the Pyramids to the Atomic Age

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Theodore von Karman: Aerodynamics

Abbot & von Doenhoff: Theory of Wing Sections

Henk Tennekes: The Simple Science of Flight

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Wylie & Balmer: When Worlds Collide

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Norbert Wiener: Cybernetics; God & Golem, Inc.

Conway & Siegelman: Dark Hero of the Information Age

A. E. van Vogt: The World of Null-A

E. E. "Doc" Smith: First Lensman

Robert Heinlein: Space Cadet

Barbara Tuchman: The Proud Tower

Peter Turchin: Ultrasociety

Nassim Taleb: Skin in the Game: Hidden Asymmetries in Daily Life

Tom Swift and his Flying Car

Barnes McCormick: Aerodynamics of V/STOL Flight

Daniel Raymer: Simplified Aircraft Design

Metropolis

Clifford Simak: City

Jane Jacobs: Dark Age Ahead

James Dunn: Driving Forces

Randall O'Toole: The Vanishing Automobile and Other Urban Myths

Robert Heinlein: For Us, the Living

Isaac Asimov: The Caves of Steel

Death of a Spaceman

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Arnold Toynbee: Civilization on Trial

H. Beam Piper: The Cosmic Computer

Robert Gordon: The Rise and Fall of American Growth

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Randall Garrett: Unwise Child

David Mindell: Our Robots, Ourselves

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Poul Anderson: Brain Wave

H. Beam Piper: The Last Enemy

Appendix C: Car regulations

In the next few years, companies that sell cars and light trucks in the United States will have to comply with increasingly stringent federal regulations on fuel economy. The government's regulations call for a required average of 54.5 miles per gallon on new cars and trucks by 2025. The requirement will vary with the size of the car or truck, so each company will face a different required fuel economy average that varies with the size-mix of its sales. This is after the Obama administration had already raised the overall required average to 34.1 mpg for 2016.

—David Henderson in *Regulation*

49CFR (meaning Title 49 of the Code of Federal Regulations), Subtitle B, Chapter V - NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION, DEPARTMENT OF TRANSPORTATION (Parts 501 - 596) contains most of the safety regulations for cars. (There are other regulations from the EPA about emissions, other laws for import duties, and so forth — this is just the part about the allowed structure of the car.) It is about six megabytes in PDF form. For a sample of the level of detail with which it constrains designers and engineers, here is Section 571.111, which concerns rearview mirrors:

S5. Requirements for passenger cars.

S5.1 Inside rearview mirror. Each passenger car shall have an inside rearview mirror of unit magnification.

S5.1.1 Field of view. Except as provided in S5.3, the mirror shall provide a field of view with an included horizontal angle measured from the projected eye point of at least 20 degrees, and a sufficient vertical angle to provide a view of a level road surface extending to the horizon beginning at a point not greater than 61 m to the rear of the vehicle when the vehicle is occupied by the driver and four passengers or the designated occupant capacity, if less, based on an average occupant weight of 68 kg. The line of sight may be partially obscured by seated occupants or by head restraints. The location of the driver's eye reference points shall be those established

in Motor Vehicle Safety Standard No. 104 (§571.104) or a nominal location appropriate for any 95th percentile male driver.

S5.1.2 Mounting. The mirror mounting shall provide a stable support for the mirror, and shall provide for mirror adjustment by tilting in both the horizontal and vertical directions. If the mirror is in the head impact area, the mounting shall deflect, collapse or break away without leaving sharp edges when the reflective surface of the mirror is subjected to a force of 400 N in any forward direction that is not more than 45° from the forward longitudinal direction.

S5.2 Outside rearview mirror—driver's side.

S5.2.1 Field of view. Each passenger car shall have an outside mirror of unit magnification. The mirror shall provide the driver a view of a level road surface extending to the horizon from a line, perpendicular to a longitudinal plane tangent to the driver's side of the vehicle at the widest point, extending 2.4 m out from the tangent plane 10.7 m behind the driver's eyes, with the seat in the rearmost position. The line of sight may be partially obscured by rear body or fender contours. The location of the driver's eye reference points shall be those established in Motor Vehicle Safety Standard No. 104 (§571.104) or a nominal location appropriate for any 95th percentile male driver.

S5.2.2 Mounting. The mirror mounting shall provide a stable support for the mirror, and neither the mirror nor the mounting shall protrude farther than the widest part of the vehicle body except to the extent necessary to produce a field of view meeting or exceeding the requirements of S5.2.1. The mirror shall not be obscured by the unwiped portion of the windshield, and shall be adjustable by tilting in both horizontal and vertical directions from the driver's seated position. The mirror and mounting shall be free of sharp points or edges that could contribute to pedestrian injury.

S5.3 Outside rearview mirror passenger's side. Each passenger car whose inside rearview mirror does not meet the field of view requirements of S5.1.1 shall have an outside mirror of unit magnification or a convex mirror installed on the passenger's side. The mirror mounting shall provide a stable support and be free of sharp points or edges that could contribute to pedestrian injury. The mirror need not be adjustable from the driver's seat but shall be capable of adjustment by tilting in both horizontal and vertical directions.

S5.4 Convex mirror requirements. Each motor vehicle using a convex mirror to meet the requirements of S5.3 shall comply with the following requirements:

S5.4.1 When each convex mirror is tested in accordance with the procedures specified in S12. of this standard, none of the radii of curvature readings shall deviate from the average radius of curvature by more than plus or minus 12.5 percent.

S5.4.2 Each convex mirror shall have permanently and indelibly marked at the lower edge of the mirror's reflective surface, in letters not less than 4.8 mm nor more than 6.4 mm high the words "Objects in Mirror Are Closer Than They Appear."

S5.4.3 The average radius of curvature of each such mirror, as determined by using the procedure in S12., shall be not less than 889 mm and not more than 1,651 mm.

Note that this is just the passenger car part; there are separate (and different) sets of specs for trucks, multipurpose vehicles, and for buses except school buses with a gross weight of 4,536 kg or less; and for school buses. This particular bit of excessive regulation is one which has long been something of a pain for flying car builders. Airplanes don't have rearview mirrors, which cause major excessive aerodynamic drag at higher speeds. Flying car makers have long tried to get the rule modified so that they could substitute rearview cameras and dashboard screens, but so far the bureaucracy will not budge.

If you wonder why many modern cars seem to have bug-eyed headlights sticking out of what would otherwise be a nicely rounded nose, it is not a Martian (or even Japanese) stylistic affectation; they serve as airflow splitters to to reduce turbulence and drag from the rearview mirrors.

Amusingly, Title 49, Subtitle B, Volume 9, Chapter XI, Parts 1400-1499: *Research and Innovative Technology Administration* are blank, reserved for future expansion. [\[281\]](#)

Appendix D: Radiation

In addition to the fact that the public is woefully misinformed on the subject of radiation, the actual units and measurements for a technical understanding of it seems needlessly complicated. This is due in part to the fact that it really is a complex subject, and partly to the fact that the scientific community changed the measurement units in the mid-70s, introducing new names for various phenomena: Gray for rad, Sievert for rem.

These units are measures of radiation exposure, and take account of an amount of radiation and the amount of tissue exposed. They do not account for time; you can use them for the total dose for an event, as in a dental X-ray is 0.5 millirem, or include time explicitly, as in average US background is 300 millirem per year.

A further complication is that what we call “radiation” is in fact a plethora of different physical phenomena. When nuclear physics began at the dawn of the 20th century, radiation was only known by virtue of being emitted from radioactive substances, and three kinds were observed. They were named alpha, beta, and gamma rays by Rutherford for differences in behavior: α -rays were bent left going through a magnetic field, β -rays bent right, and γ -rays did not bend at all. Not much earlier, Röntgen had produced what he called X-rays in a cathode ray tube.

It turns out that β -rays and cathode rays were essentially the same things, high-energy electrons, and γ -rays and X-rays were similarly the same, high-energy photons. The differences were the source and the typical energy. α -rays turned out to be helium nuclei. Today we tend to think of them as particles, and “rays” sounds old-fashioned.

Together with a few similar particles such as protons, we call these ionizing radiation, which by definition means they are capable of breaking bonds in molecules and thus doing damage in biological systems. Photons which do not have enough energy to break bonds, such as ordinary light or radio waves, are excluded. The threshold is ultraviolet, whose photons are just more energetic than visible. About 0.5% of sunlight is thus ionizing radiation; it will give you a sunburn and and bleach (and disinfect) clothing on a clothesline.

In very rough terms, the amount of radiation damage in tissue is proportional to the total energy of the particles. The units of exposure are measures of energy deposited in a given mass of tissue: 1 Gray is one Joule of energy per kilogram of mass. The older unit, rad, is one erg per gram. At a closer look, it turns out that the different forms of radiation have somewhat varying effects for the same amount of energy. The Sievert (or rem) is a measure of the effective dose after the difference is taken into account. For X-rays (or UV light, or gammas), the factor is 1; one Sievert equals one Gray of X-rays. For alphas, the factor is 20; for betas, it's 1; for neutrons, it varies, 5 for slow, 10 for fast. Neutrons are not themselves directly ionizing, but can create transmutations and secondary radiation of the previous kinds via interactions with nuclei in the target material. The older units of exposure work the same way: One Gray is 100 rad; one Sievert is 100 rem. Unfortunately the new units are huge; typical exposures are most easily measured in millirem or microSievert.

old unit	new unit	effect
600 rem	6 Sv	in pacem requiescat
400 rem	4 Sv	LD50 - critical condition
100 rem	1 Sv	radiation sickness onset
50 rem	500 mSv	threshold (protracted)
10 rem	100 mSv	threshold (acute)
1 rem	10 mSv	full-body CT scan
300 mrem	3 mSv	natural background (annual)
100 mrem	1 mSv	flight crew (annual)
10 mrem	100 μ Sv	a day at the beach (UV)
1 mrem	10 μ Sv	dental X-ray

Numbers are approximate; a dental X-ray varies from 0.5 millirem to 1.5, for example. 3 mSv is an average background in the US; natural background varies markedly depending on where you are in the world, ranging up to 260 mSv (26 rem) per year. The levels labeled “threshold” are the most likely estimates for levels below which there is no significant

carcinogenesis. Acute means you get the dose all at once; protracted means you accumulate it over months or so.

Higher exposures are well-studied. One massive study followed 100,000 survivors of the Hiroshima bombing, 20,000 controls living in similar circumstances but not present at the time, and 70,000 of their children for 60 years following the irradiation. [\[282\]](#) The bomb dose was of course acute in form. The average loss of life expectancy among those who received high doses, in the 1 Sv (100 rem) range, was about a year; for those who got 100 mSv (10 rem), the decrease was a month and a half.

The rate of increase in (fatal) cancer risk is 0.08% per full rem (1000 millirem) of acute exposure, [\[283\]](#) or 0.02% to 0.04% per full rem of protracted exposure. In the Linear No Threshold hypothesis, you start counting from zero; someone in the 2 rem (20 mSv) per year zone of the Fukushima plume might have a 0.06% higher than before chance of dying of cancer. Since the normal cancer rate (in Japan) with no exposure is 20%, their total risk would then be 20.06%. If as is more likely there is a threshold, 2 rem in a year is well below any reasonable estimate of it, and there would simply be no effect whatsoever.

One way of studying low radiation doses is simply to gather statistics about people living with different natural background rates. According to the World Nuclear Association,

Several places are known in Iran, India and Europe where natural background radiation gives an annual dose of more than 100 mSv to people and up to 260 mSv (at Ramsar in Iran, where some 200,000 people are exposed to more than 10 mSv/yr). Lifetime doses from natural radiation range up to several thousand millisievert. However, there is no evidence of increased cancers or other health problems arising from these high natural levels. The millions of nuclear workers that have been monitored closely for 50 years have no higher cancer mortality than the general population but have had up to ten times the average dose. People living in Colorado and Wyoming have twice the annual dose as those in Los Angeles, but have lower cancer rates. Misasa hot springs in western Honshu, a Japan Heritage site, attracts people due to having high levels of radium (up to 550 Bq/L), with health effects long claimed, and in a 1992 study the local residents'

cancer death rate was half the Japan average. A study on 3000 residents living in an area with 60 Bq/m³ radon (about ten times normal average) showed no health difference.

There is one obvious reason we need to understand this better than we do, nuclear power completely aside. There is a value to X-rays and other radiation-based examination as a medical diagnostic tool, but their use is limited for exposure concerns. If we had a better handle on thresholds we might be able to optimize that.

There was a Low Dose study line item in the Department of Energy's Science budget, explicitly addressing exactly this concern, up until 2009. It vanished, for presumably political reasons that remain obscure. The research appears to have been completely defunded by 2011, and the results were never made available.

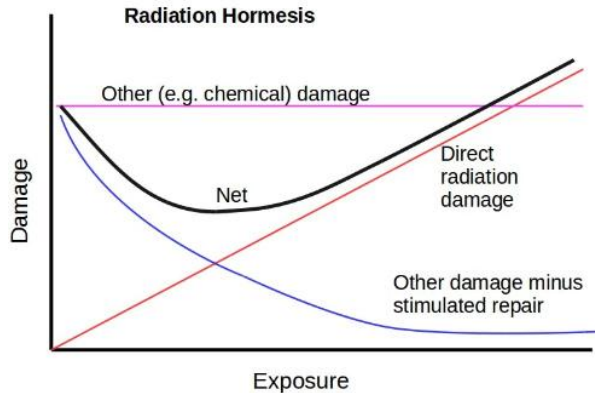
Hormesis

I have had radiation sickness, and in all probability, so have you. In our cases, we called it a sunburn. Luckily, the UV portion of sunlight, which is the only part which is ionizing radiation, is only about half a percent of the total energy, and it only penetrates about 4 millimeters into the skin. (And luckily, 70% of even that is absorbed by the *stratum corneum*, the layer of dead cells that covers the living epidermis.) Even so, overexposure to sunlight is by far the leading cause of radiation-associated maladies, including melanoma and other skin cancers. Should we all go live in caves, or at least never go outside?

Certainly not. If you get no exposure at all, you are at high risk of rickets and bone disease. You are better off with increasing exposure up to a certain point, as the radiation stimulates the cells to activate various defensive and repair mechanisms, notably Vitamin D. In fact, a recently-published study from Sweden found that *avoiding* the sun is as bad for you as smoking.

[\[284\]](#) Remember that the vast majority of cancer (except skin cancer) is not caused by radiation, but by chemical agents, starting with oxygen. The number of DNA breaks caused by the US average background radiation level is on the order of 10 per cell per year; the number caused by completely normal metabolic chemistry is 25 million. Above the optimal

point, of course, direct damage from radiation overwhelms the defensive and repair mechanisms, and you are worse off with increasing dose; but that's much much higher than background.



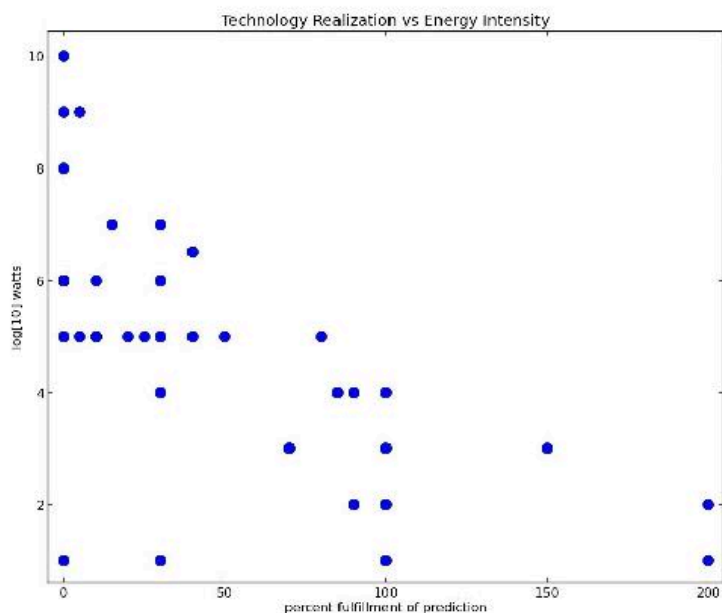
This concave shape of a dose-response curve in toxicology is called *hormesis*. The hormesis curve looks a lot like the airplane power curve, and for the same reason: it is the sum of two components, one rising and one declining. In the case of UV exposure, hormesis is the completely accepted scientific orthodoxy. [\[285\]](#) The hormetic shape is actually the default expected form. [\[286\]](#) Thus there is a hypothesis that the other, more penetrating forms of ionizing radiation might also exhibit a hormesis curve. Two rem over the course of a year might actually reduce your chance of cancer by 0.05% instead of increasing it.

Unfortunately, this would fly in the face of the Linear No Threshold hypothesis, enshrined as doctrine for the past 70 years. Furthermore, it is extremely hard to study, as the effect on cancer rates according to the LNT or hormesis, whichever if either is real, is so small as to be lost in the noise of actual rates from other causes. Furthermore it is quite likely that some forms of cancer (e.g. thyroid) are exacerbated while others are suppressed by the same overall dose, and that some people (e.g. children) are more susceptible than others. There is no “one size fits all” bottom line. This makes epidemiological studies difficult to interpret.

Even so, the evidence is quite strong that the LNT is wrong, and there is fair evidence for hormesis. I asked a friend who is a top X-ray physicist, and he replied, “I hope hormesis is true.”

So do I.

Appendix E: Energy Intensity of Predicted Technologies



Rated by what percentage of the expected development we got, or if a technology flatlined what percentage of the past 50 years it kept developing on expected schedule. Energy intensity is log base 10 of watts: a human at subsistence is 100 watts, or 2; an American today (or in 1975) is ten kilowatts, or 4. A car gets rated 4 even though it may have a multi-hundred kW engine, because at average cruise it is only putting out on the order of tens. An airplane with the same nominal horsepower gets a 5, though, because you run the airplane engine at more than half power all the time. Admittedly both the coordinates for each technology are not only estimates but somewhat subjective estimates. Even so I was quite surprised at the shape of the resulting graph; I had expected a only mild correlation. I have refrained from updating any estimate since seeing the graph.

- Pocket telephones: 200% Not only are they more common now than most SF writers would have predicted, but they do more. They use little energy, even pro-rating your share of the tower and network. 1.

- Home-based videophones (also used for reading and commerce): 100%; 2.
- Space stations: 40%; we have one but they expected more, with commercial traffic. 6.5.
- Lunar landings: 15%; not only did we flatline, we zeroed. 7.
- Nuclear rockets: 5%; 9.
- Lunar base: 0%; 8.
- Interplanetary travel: 0% (manned landings); 9.
- Interplanetary colonies: 0%; 10. This is virtually impossible without nuclear rockets.
- Cars: 100%; 4.
- Self-driving cars: 100%, meaning we got just about as far towards them as the best-informed guesses; 4.
- Hovercraft: 10%, a few sport vehicles and ferries, but no major personal transportation; 5.
- Private planes: 30%; 5.
- Convertible planes: 10%; 5.
- VTOL flying cars: 0%; 6.
- Transportation 1000 mph and one cent per mile: 30%; we got half the speed and a mile costs a nickel; 6.
- Highways in decline as air vehicles predominate: 20%, as they are in decline but mostly from mismanagement rather than air travel; 5.5 as an average for air travel.

- Batteries: 70%; 3. Chemical batteries have come a long way; they expected electric cars.
- “Atomic” batteries: 0%; 5. The reasonable expectation was for something 100 to 1000 times as good as we have now.
- Fusion power: 0%; 6. “Too cheap to meter.”
- Wireless energy transmission: 10%; 5.
- Space-based military: 30%; nuclear ICBMs are the defining background of all things military, and space-based recon is common. But they expected military space stations and moon bases. 7.
- Cyborgs: 50%, mostly for medical instead of enhancement; 4.
- Robots: 100%, because Asimov nailed the current status with “will neither be common nor very good in 2014, but they will be in existence.” 3.
- Automation eliminating jobs: 50%; 4.
- Household robots: 90%; 2.
- Industrial robots: 100%; 3. The difference between this and “automation” has to do with the expectations associated with the terms.
- Translating machines: 90%; 4. Workable translation is a “big data” phenomenon and implies a datacenter, not a PC.
- Artificial intelligence: 80%; 5. Even bigger datacenter.
- Global library: 150%; 3. Unlike an AI, they expected a library to be shared.
- Computers: 200%; 2. This one is your PC or tablet.

- “Atomic” power: 25% with the flatline. 5.
- Undersea cities: 0%; 6.
- Floating cities: 20% (think cruise ships). 5.
- Domed cities: 5%, mostly stadiums. 5.
- Sea mining: 10%, mostly oil wells. 6.
- Innovative housing technology: 40%; 5.
- Automatic home meal preparation: 30%; mostly the microwave and beverage makers combined with prepackaged meals. 3.
- Major substitution of synthetic food for agriculture: 50%, where I’m taking this to include the industrialization and energy intensification of agriculture itself, which is clearly moving in the direction of factory-produced food. 5.
- Contraception, revising relations between the sexes: 100%; 1.
- Cures for cancer, the common cold, and tooth decay: 30%; 1.
- Psychology and education a hard science: 0%; 1.

Appendix F: Flying Cars

This list is restricted to machines that have been actually built and flown, or are currently in serious development. Dates are of first flight, where available. Airspeeds are cruise; an airspeed of 0 means it didn't actually sustain free flight (but did something more than just sit, e.g. a tethered test). We exclude vehicles much larger (or smaller) than car-sized; thus you don't see "flying Segways" such as the Hiller Platform or flying buses such as the X22-A. If I included all the proposed, modelled, almost-built, and conceptual flying cars that have been advanced (but not actually flown) over the 20th century, the list would be at least 10 times as long, even with my restrictions. The modes are:

mod: modular, a car designed to have wings attached, but which drove off without them

trl: trailer, like modular, but the wings were configured to fold up into a trailer and be taken with the car

fld: the wings fold for road travel

ret: retractable wings that disappear into the body of the car

rsw: removable stowable wings; i.e. the car can carry them on the road

vtol: Not roadable, but point-to-point by virtue of not needing a runway

Date	Name	Mode	Airspeed	Remarks
1917	Autolandplane	mod	0	Glenn Curtiss; short hops
1921	Avion-auto	fld	90?	Rene Tampier
1930	Car-plane	fld	90?	George C Spratt
1938	Arrowbile	mod	105	Waldo Waterman (6 built)
1938	Pitcairn AC-35	fld	75	roadable autogyro
1939	Roadable Airplane	mod	110	Theodore P. Hall
1944	Convair 103	mod	110	Spratt & Stout
1946	Plane-Mobile	fld	80	Zuck & Whitaker
1946	Southernaire	mod	110	Hall and Willis Brown
1946	Convair 116	mod	120?	Hall and William Stout

1946	Plane-mobile	fld	90?	Daniel Zuck
1947	ConvAirCar	mod	130	= Convair 118 (Hall, <i>et al</i>)
1947	Airphibian	mod	110	Robert E. Fulton
1949	<i>the</i> Aerocar	trl	100	Molt Taylor (5 built)
1951	Hiller Hornet	vtol	75	rotor-tip-jet helicopter
1952	Aerauto PL.5C	fld	100	Luigi Pellarini
1953	Autoplane	fld	90	Leland D Bryan
1956	Versatile I	fld	120	Lewis A Jackson
1957	Road Wing	fld	120	Bruce K Hallock
1957	Vertol VZ-2	vtol	170	Army research tilt-wing
1958	Doak VZ-4	vtol	190	tilt-ducted-fan
1958	VZ-8 Airgeep	vtol	40	Piasecki
1959	Aero Car	fld	85	Joseph L Halsmer
1959	VZ-9 Avrocar	vtol	0	“flying saucer”
1962	VZ-8 Airgeep II	vtol	70	Airgeep with turbines
1963	Concept-7	fld	130	Lewis A Jackson
1964	Skyway AC-35	fld	134	updated Pitcairn AC-35
1965	Wagner Aerocar	vtol	80?	roadable helicopter
1965	Ryan XV-5	vtol	547	fan-in-wing jet
1973	AVE Mizar	mod	125?	Pinto + Cessna Skymaster
1976	de Lebouder	mod	110	wings on a Vespa 400
1990	Moller M200X	vtol	30?	mini flying saucer
1998	CarterCopter	vtol	160	autogyro
2002	Moller M400 Skycar	vtol	0	tethered hops only
2003	Volante	trl	150	K. P. Rice

Since about a decade ago, there has been a renewed interest in flying cars, and a number of projects and companies have started work on new ones. There are many more than listed here that have not, to my knowledge, flown yet. Date still means first (untethered) flight:

Date	Name	Mode	Airspeed	Remarks
------	------	------	----------	---------

2011	Rutan BiPod	rsw	30?	taxi-test hops only
2012	Terrafugia Transition	fld	105	in flight testing
2012	PAL-V	fld	100	roadable autogyro
2013	Volocopter	vtol	54	18-rotor electric
2013	Aeromobil	ret	125	Slovakian, in flight test
2015	Carplane	rsw	136	German, in flight test
2015	Commuter Craft	fld	160?	US, in flight test
2015	Ehang 184	vtol	60	1-place quadcopter
2016	UrbanAero AirMule	vtol	65	updated Airgeep
2017	Lilium	vtol	186	canard w/ TE EDFs
2018	KittyHawk Cora	vtol	90	Winged 12-copter
201x	DARPA Transformer	vtol	130?	Lockheed Martin

The Ehang and Lilium have flown empty under radio control; the Volocopter's first piloted flight was in 2016.

There is a flying taxi that is the subject of a collaboration between Uber, NASA, and Bell Helicopter under the name Elevate, which is rumored to have flown a prototype. The KittyHawk has been under secret development in New Zealand under the company name of Zephyr; it is a pusher airplane of fairly modern design with 12 electric props attached to the wings for vertical thrust.

Besides these which have actually flown, in development are the Vahana by Airbus, which is a modular system similar in concept to the DARPA transformer (which has itself been renamed ARES and moved to latter-stage development), the Cormorant by Urban Aero, Jetpack Aviation's 12-prop hexacopter (6 coaxial pairs, similar to Ehang's 4), the Workhorse SureFly, a 4-coaxial-pairs hybrid (gas/electric) quadcopter, Lilium Aviation's canard jump jet with 36 electric ducted fans at the wing trailing edges, AirSpaceX's Mobi-one six-prop tilt-wing, Joby aviation's electric VTOL with 12 tilt-rotors, Terrafugia's TF-X, and Zee.Aero whose patents look like a dual inline octocopter but are keeping actual development close to the chest. By the time you read this, it will be out of date...

Appendix K: Kardasheff levels

Just to put the scale in context. Numbers are log watts, so each line is ten times the power of the previous one. Numbers are only estimated to within a factor of 10.

1. Ten watts is the metabolic rate of a small animal, such as a kitten.
2. One hundred watts is the average metabolic rate of a human. 250 watts is an electric bike motor.
3. A kilowatt is comparable to a horsepower. It is the average electric power of a home in the US.
4. Ten kilowatts is the motor in a Vespa, the average total power use per capita in the US.
5. 100 kW is the range of a small car engine, or a light sport category airplane.
6. A megawatt is the range of a tractor-trailer or a small jet. The flying car you should have.
7. Kardasheff level 0, extrapolated. 100,000 pre-literate humans. The Titanic.
8. One GE90 airliner engine. Filling your car's gas tank.
9. A nuclear power plant. Total human energy use when Henry Adams was born.
10. The Three Gorges Dam generating capacity.
11. All nuclear power plants in US.
12. Total electric power in US. The total human food stream.

13. Total human energy use today. One Orion spacecraft.
14. Geothermal power emitted by the Earth. Total human energy use today if the Henry Adams curve had not flatlined in the 70s.
15. Solar power hitting the Earth as ionizing UV.
16. Solar power striking Mars.
17. Total solar power striking the Earth. Kardasheff level one. 1 kg/sec mass-energy conversion.
18. Solar power striking Mercury.
19. Total human energy use, if we used the same amount of uranium we now do chemical fuel.
20. ... if we used the same amount of hydrogen in fusion we now use chemical fuel. 1 ton/sec mass-energy conversion.
21. Total human energy use in 2400 if we regained the Henry Adams curve.
22. ... if we had the same amount of mass-energy conversion we now use chemical fuel.
23. ... if we mined Jupiter for hydrogen for fusion at the same proportional rate we now mine Earth for chemical fuel.
24. ... in 2550 if we regained the Henry Adams curve.
25. ...if we mined Jupiter for mass-energy conversion at the same proportional rate we now mine Earth for chemical fuel.
26. ... if we mined the Sun for hydrogen at the same proportional rate we mine the Earth for chemical fuel.

27. Kardasheff level 2; a Dyson Sphere. At 10 billion kg/sec mass-energy conversion, it represents the rate the Sun consumes itself for hydrogen fuel.
28. ... if we mined the Sun for mass-energy conversion at the same proportional rate we now mine Earth for chemical fuel.
29. ... if we mined the Sun for mass-energy conversion at the same rate it consumes itself for hydrogen fuel.

Appendix P: Photo credits

I try to credit Army, Navy, NASA, etc photos even though they are in the public domain. National Air & Space Museum photos are copyright.

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- The World of Tomorrow
 - Tom Swift books, author
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 - real wages data from Turchin, *Ages of Discord*, figure 3.3. graph by author
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 - real disposable personal income growth rate data from FREDgraph

- piston-engine shipments data from General Aviation Manuf. Assn.
- Henry Adams Curve data from Energy Information Administration
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- energy intensity see appendix E
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 - nanotechnology data from google n-grams
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 - Plenty of Room data from google scholar
 - R&D funding source AAAS
 - F&M jobs data USDA, BLS via Mark J Perry
 - PhDs data NSF
 - government spending on education (courtesy Chris Cantrell, usgovernmentspending.com)
- Cold Fusion?
 - F&P heat burst is derived from Fig. 9a in Fleischmann, M., et al., *Calorimetry of the palladium-deuterium-heavy water system*. J. Electroanal. Chem., 1990. 287: p. 293.
 - DOE conclusions, author
- Forbidden Fruit
 - Bruce Hallock and the Road Wing (courtesy Austin Hallock)
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- regulations data Manufacturers Alliance for Productivity and Innovation (MAPI)
- US GDP growth data FredGraph, Fraser Institute
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 - accelerations (2) author
 - flows simulated with the SU2 open-source fluid dynamics program at Mach 0.2, and visualized with the open-source ParaView viewer.
 - inverted power curves by author inspired by an exposition by Denker

- skyvector.com
- Dialogue Concerning the Two Great Systems of the World
 - Robinson R44, by the author in Piahia, NZ
 - AutoGyro Cavalon (and author), photo: Sandra Hall at KW29
 - Jevons (author)
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 - trip freq data from above
 - travel times data from above
 - revealed pref data from above
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- Seaborg's speck (courtesy Eric Norman; see *E. B. Norman, K. J. Thomas, K. E. Telhami, Amer. Journ. Phys. Vol. 83, Oct. 2015, pages 843-845.*)
- plant construction permits, data EIA
- US PhDs in nuclear physics, data NSF
- Jet Age
 - power/speed data collected by author (2)
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 - Moller Skycar 400 (courtesy Paul Moller)
 - ARES (courtesy DARPA)
 - Urban Aeronautics AirMule (Wikimedia / Timur Saban (CC))
 - power vs disc loading (2) see Barnes W. McCormick, Jr: *Aerodynamics of V/STOL Flight* for the semi-empirical formula.
 - Ryan XV-5B (NASA)
 - airplane mode author
 - Terrafugia Transition courtesy Terrafugia
 - Aeromobil courtesy Aeromobil
 - TERN (DARPA / ONR)
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- When Worlds Collide
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- Failure of Feedback
 - Ike Marvelous Powder of Life: *Ozma of Oz* is in the public domain
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 - heli and pad (courtesy Peter de Graaf, *(New Zealand) Northern Advocate*)
- Tom Swift and His Flying Car
 - Schübeler DS-215-DIA HST courtesy Schübeler
 - blown wing, author / SU2 / Paraview
 - Lifting Bodies. (NASA)
 - flying car, author using open-source Povray
- Metropolis
 - wind, author
 - heights, author
 - Futurama, photo by Richard Garrison: © The Edith Lutyens and Norman Bel Geddes Foundation, used with permission
 - Elm St. Dallas, by the author
 - happiness, data as reported by Brian Berry and Adam Okulicz-Kozaryn in the Washington Post Wonkblog
 - PBY-5A Catalina: U.S. Navy Naval History and Heritage Command
- Escape Velocity
 - Airliner speed curve, see appendix A
 - V-2 fuel pump, by the author at Peenemunde
 - “Discovery II” (NASA Glenn Research Center)

- Koken barber chair (courtesy Doug Schmidt Antiques)
- To Singularity, and Beyond
 - Per capita GDP growth rates data FREDgraph, plot author
 - Moore's Law, data Kurzweil, author
 - Hanson, data Hanson
- The Second Atomic Age
 - U238 cross section vs neutron energy, Los Alamos National Labs
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 - Hagelstein and Widom, by the author at MIT
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 - space pier, author
 - Earth by NASA, with sunshades by the author
- Rocket to the Renaissance
 - orbit speeds, author
- Radiation
 - Hormesis curve, schematic by the author

Footnotes

[1] *Edison's Conquest of Mars*, by Garrett P. Serviss, serialized *New York Evening Journal* 1898.

[2] David Gelernter, *1939: the Lost World of the Fair*, Free Press, 1995, p.343

[3] *Things to come: a film by H. G. Wells*. Macmillan, 1935

[4] *Green Light for the Age of Miracles*, by Waldemar Kaempffert, The Saturday Review, April 22, 1944, p. 14.

<http://www.unz.org/Pub/SaturdayRev-1944apr22-00014>

[5] <http://www.nytimes.com/books/97/03/23/lifetimes/asi-v-fair.html> [6]

This quote from a 1964 BBC interview.

[7] <http://en.wikipedia.org/wiki/NERVA> [8]

http://en.wikipedia.org/wiki/Project_Pluto [9] <http://www.mining-technology.com/features/feature46357/>

[10] The spelling was changed to “Rosie” in the 1980s reappearance of the series. She is clearly modeled on Hazel of the contemporary live-action sitcom and earlier comic strip.

[11] The Civilian Version, the Vought V-173, was flown by, among other test pilots, Charles Lindbergh.

[12] National Advisory Committee for Aeronautics report 431:

Characteristics of Clark Y airfoils of Small Aspect Ratios [13]

<http://www.williammaloney.com/Aviation/MidAtlanticAirMuseum/CusterChannelwing/index.htm> accessed 11 Oct 2011

[14] Charnov, *From Autogyro to Gyroplane*, p. 43

[15] Amelia Earhart, “Your Next Garage may House an Autogiro,” *Cosmopolitan* 91, #2, Aug 1931. It is likely that the article was actually ghost-written by Pitcairn’s ad agency.

[16] General Aviation Manufacturers Association:

http://www.gama.aero/files/statistical_data_1973_498b99d81d.pdf, p. 7

[17] <http://airandspace.si.edu/collections/artifact.cfm?id=A19610070000>

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<http://www.dtic.mil/dtic/tr/fulltext/u2/417836.pdf> [19] Paul Hoversten,

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Magazine, <https://www.airspacemag.com/need-to-know/why-do-helicopter-pilots-sit-in-the-right-seat-243212/>

[20] <http://theeconomiccollapseblog.com/archives/rotting-decaying-and-bankrupt-if-you-want-to-see-the-future-of-america-just-look-at-detroit> [21]

<http://www.nationaljournal.com/next-america/population-2043/it-s-about-as-dangerous-here-now-as-it-is-in-mexico-20150304>

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<http://motherjones.com/kevin-drum/2011/10/future-of-innovation>, accessed 10 Oct 2011

[24] *The Machine Stops* was first published in The Oxford and Cambridge Review in 1909, and between hard covers in 1928. It may be read online at <http://archive.ncsa.illinois.edu/prajlich/forster.html> [25] A comprehensive overview can be found at

<http://slatestarcodex.com/2017/02/09/considerations-on-cost-disease/>

[26] Robert W. Prehoda, *Designing the Future: The Role of Technological Forecasting*, Chilton, 1967, p55

[27] see

<http://www.census.gov/hhes/www/income/data/historical/household/>

[28] <http://research.stlouisfed.org/fred2/graph/?id=A229RX0>, frequency: annual, Units: percent change from a year ago; OLS linear regression from 1962 by the author [29] See Appendix A for specifics.

[30] US EIA <http://www.eia.gov/todayinenergy/detail.cfm?id=11951>

[31] Your humble narrator was judge and awardee selector.

[32] In 2014 a laboratory prototype of a nanoscale logic machine, assembled using a variety of ingenious techniques, was reported by J. Ellenbogen and associates at Mitre and Harvard.

<http://www.pnas.org/content/111/7/2431.full> [33]

<http://calteches.library.caltech.edu/1976/1/1960Bottom.pdf>; see also <http://www.nature.com/nnano/journal/v4/n12/full/nnano.2009.356.html>

[34] Regis, Ed, *Great Mambo Chicken and the Transhuman Condition*, Addison-Wesley, 1990, p. 119

[35] Drexler, K.E. (1986) *Engines of Creation: The Coming Era of Nanotechnology* New York: Anchor Press/Doubleday.

[36] For the basic capability to be expected, see *Nanosystems* Fig. 14.8: a 1-kg system can produce 1 kg of product in an hour. Let it multiply

exponentially for 2 days and you have 2.8×10^{14} machines, or 280 billion tonnes of nanomanufacturing equipment. The rule of thumb is that you replicate until you have 69% of the mass of the target product in replicators, and then set them all to work making the target. A more detailed estimate involves deciding what are appropriate assumptions involving feedstocks, transportation, and so forth, but this will give you an idea of the raw creative power of an autogenous technology. *It is a possibility.*

[37] <http://clinton6.nara.gov/2000/01/2000-01-21-remarks-by-the-president-at-science-and-technology-event.html> [38] Over 90% of the NNI budget is actually spent by NSF, DoD, DoE, and NIH. Fritz Alhoff, ed, *Nanoethics*, Wiley, 2007, p. 83

[39] For which, among other things, your humble narrator did a study of the applications of nanotechnology to flying cars.

[40] See for example K. Eric Drexler, Ph.D.; David Forrest, ScD.; Robert A. Freitas Jr., J.D.; J. Storrs Hall, Ph.D.; Neil Jacobstein, M.S.; Tom McKendree Ph.D.; Ralph Merkle Ph.D.; Christine Peterson: *On Physics, Fundamentals, and Nanorobots: A Rebuttal to Smalley's Assertion that Self-Replicating Mechanical Nanorobots Are Simply Not Possible* <http://www.imm.org/publications/sciamdebate2/smalley/> See also Drexler, *Radical Abundance*, (PublicAffairs, 2013) chapter 13.

[41] Duarte, Crawford, Stern, Haidt, Jussim, and Tetlock, "Political Diversity Will Improve Social Psychological Science," *Behavioral and Brain Sciences*, to appear 2015; preprint at http://journals.cambridge.org/images/fileUpload/documents/Duarte-Haidt_BBS-D-14-00108_preprint.pdf [42]

<http://www.theguardian.com/society/2016/apr/07/the-sugar-conspiracy-robert-lustig-john-yudkin> [43] What if It's All Been a Big Fat Lie?

<http://www.nytimes.com/2002/07/07/magazine/what-if-it-s-all-been-a-big-fat-lie.html?pagewanted=all> [44] Then known as "the United States National Museum."

[45] http://www.libraries.wright.edu/special/wright_brothers/1903_flyer/history.php Curtiss' suit was denied, and he ultimately bought out the Wrights patent for \$1,000,000 to found the Curtiss-Wright aircraft company.

[46] http://en.wikipedia.org/wiki/Wright_brothers; Langley also got about \$20,000 in private funding. In current dollars, roughly \$28,000 (Wrights) vs

\$1,400,000 + \$560,000 (Langley).

[47] Kealy, Terrence, *The Economic Laws of Scientific Research*, Palgrave Macmillan (1997) [48]

<http://browse.oecdbookshop.org/oecd/pdfs/free/1103011e.pdf>, Table 2.6, p. 85

[49] The full title is *A Nation at Risk: The Imperative for Educational Reform*, the 1983 report of Ronald Reagan's National Commission on Excellence in Education.

[50] <http://ftp.iza.org/dp5367.pdf>, pp3-5

[51] <http://www.nsf.gov/statistics/infbrief/nsf12303/nsf12303.pdf>, tables 1 & 2

[52] At the high end, at least. Increasing high-school dropout rates seem to match declining productivity figures somewhat better.

[53] <http://archive.darpa.mil/grandchallenge05/GC05winnerv2.pdf> [54]

(E.g. Wollheim, *Secret of Saturn's Rings*, Chapter 5: *Cosmic Hitchhike*.)

Matching orbits with the asteroid uses as much fuel as it would have taken to duplicate its trajectory without it; landing and taking off again are superfluous and waste even more fuel.

[55] New York Times: p. 12. January 13, 1920.

[56] The New York Times, July 17, 1969, p. 43, "A correction".

[57] <http://blogs.nature.com/news/2014/05/global-scientific-output-doubles-every-nine-years.html> [58]

J Storrs Hall, *Nanofuture* [59] Krivit, S, *The Rebirth of Cold Fusion*, Pacific Oaks, 2004, p. 70. see also Mallove, E: *Fire from Ice*, Wiley, 1991, p. 40.

[60] For a very rough (and extremely conservative) estimate, guess that there was as much heat produced as a 14-ounce Bernzomatic propane cylinder does: 18 megajoules. Roughly as much more energy would have been produced as neutrons and gammas as heat. 5 Sieverts, a lethal dose, comes to 500J of absorbed radiation per 100kg body. There would have been enough radiation, if evenly distributed, to kill 36,000 people.

[61] J. Rafelski and S.E. Jones, "Cold Nuclear Fusion," *Scientific American*, 257: 84-89 (July 1987).

[62] Steven Krivit, *The Rebirth of Cold Fusion*, Pacific Oaks, 2004, p72

[63] F & P had wanted to end the title with a question mark, but bowed to pressure to omit it.

[64]Fralick, Decker, and Blue (1989) NASA TM 102430. Fralick had been looking for neutrons, which were not found, and so didn't publish in the open literature, but merely filed their results as a NASA technical memo. They did find excess heat, though, a 15C temperature rise in the deuterium experiment as compared to the light-hydrogen control.

[65]Miles, M and Hagelstein, P: New analysis of MIT Calorimetric Errors, *J. Cond. Mat. Nuc. Sci.* **8** 2012 pp 132-138

[66]Over the 80s, fusion funding had averaged about a billion a year in 2015 dollars.

[67]<http://www.economist.com/news/briefing/21588057-scientists-think-science-self-correcting-alarming-degree-it-not-trouble> — and don't even get me started on the psychology and other soft "sciences" literature.

[68]<http://www.nature.com/news/seven-days-3-9-august-2012-1.11139#comment-48984>

[69]Advanced-to-Revolutionary Space Technology Options – The Responsibly Imaginable (NASA/TM–2013-217981) [70]

<http://www.deseretnews.com/article/103053/PERSONAL-ATTORNEY-OF-PONS-FLEISCHMANN-IS-BEING-PAID-BY-THE-U.html?pg=all> [71]

Roulette, T., J. Roulette, and S. Pons, *Results of ICARUS 9 experiments Run at IMRA Europe*, in ICCF6

[72]Thomas W. Grimshaw, Ph.D, *Evidence-Based Public Policy toward Cold Fusion: Rational Choices for a Potential Alternative Energy Source*, University of Texas at Austin, 2008

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<http://arxiv.org/pdf/1309.4731.pdf> [75]

<http://www.publicpurpose.com/freeway1.htm> [76]Austin B Hallock, *Sky Full of Dreams: the Aviation Exploits, Creations, and Visions of Bruce K. Hallock* [77]

In his book *Flying Cars: the True Story* [78]Reason, Aug 1984, pp40-42. see <http://www.unz.org/Pub/Reason-1984aug-00040>

[79]National Highway Traffic Safety Administration (July 1972). PB 211-015: Evaluation of the 1960–1963 Corvair Handling and Stability.

[80]Macroeconomic Impacts of Federal Regulation of the Manufacturing Sector, NERA Economic Consulting, commissioned by MAPI, Aug 2012, http://www.mapi.net/system/files/NERA_MAPI_FinalReport_0.pdf, p. 96

[81]Such as Glenn Reynolds:

<http://www.usatoday.com/story/opinion/2016/05/12/technological->

progress-stagnation-regulatory-explosion-1970s-column/84225066/

[82] <http://www4.ncsu.edu/~jjseater/regulationandgrowth.pdf> [83] Djankov, McLiesh, and Ramalho, 2006, "Regulation and Growth." *Economic Letters* 92 (3): 395–401.

[84] S. Peltzman, "An Evaluation of Consumer Protection Legislation: 1962 Drug Amendments." *J Pol Econ* 81(5), 1049-1091.

[85] As a driver, of course, you should always wear a seatbelt. As a pedestrian, you would be safer if seatbelts were prohibited. Guess who is actually at greater risk?

[86] Currently, new drug approval averages 13 years.

[87] Thomas Hager, *The Demon Under the Microscope: From Battlefield Hospitals to Nazi Labs, One Doctor's Heroic Search for the World's First Miracle Drug*; see an exegesis at

<http://specieaeternitatis.blogspot.com/2016/08/history-fda-and-cognitive-biases.html> [88] in a study by the Small Business Administration in 2010:

"The Impact of Regulatory Costs on Small Firms"

<https://www.sba.gov/advocacy/impact-regulatory-costs-small-firms> [89]

<http://www.econlib.org/library/Enc1/AirlineDeregulation.html> [90]

http://www.rita.dot.gov/bts/sites/rita.dot.gov/bts/files/publications/national_transportation_statistics/html/table_01_40.html [91] 3.1 deaths per billion km for cars, 0.05 for airliners. [Wikipedia]

[92] Fredgraph variable MEHOINUSA672N

[93] see A. Barton Hinkle, http://www.richmond.com/opinion/our-opinion/bart-hinkle/article_a71d0b9a-4f33-5972-96c2-d61baf3768d8.html

[94] Yes, a real case. See Philip Howard, *The Death of Common Sense*, Random House, 2011

[95] e.g. Harvard Law Review article "The Administrative State Under Siege."

[96] <http://www.172guide.com/History.aspx> [97] The Cessna 172 Skyhawk is the most successful model of private plane, with more units built than any other model from any manufacturer.

[98] <http://www.econlib.org/library/Enc/Liability.html> [99]

<http://www.forbes.com/sites/businessaviation/2012/08/29/did-economics-and-politics-cut-the-heart-out-of-personal-aviation/>

[100] It varies wildly with specialty and geography, ranging roughly from \$20,000 to \$200,000 a year. It's actually not as bad now as it was last

century, since many states (33 at last count) have passed liability limitation laws.

[101] https://www.faa.gov/uas/model_aircraft/

[102] <http://www.wsj.com/articles/l-gordon-crovitz-amazons-drones-exiled-to-canada-1428270643>

[103] <http://fusion.net/story/257423/everyone-is-suing-uber/>

[104] AOPA Pilot April 2016 p.20

[105]

<https://www.dlapiper.com/en/us/insights/publications/2016/03/commercial-use-of-drones/>

[106] *The New Industrial State*, Princeton, 1967

[107] See Simler and Hanson, *The Elephant in the Brain*, chapters 13 and 14 in particular. See also Caplan: *The Case Against Education* [108] e.g., the god Baal got transmogrified into the demon Beelzebub.

[109] http://articles.latimes.com/1989-10-22/books/bk-726_1_bill-mckibben/2

[110] <https://www.atsdr.cdc.gov/phs/phs.asp?id=79&tid=20>

[111] Bitman, Cecil, Harris and Greis, *Nature*, 1969, 224: 44-46

[112] Cecil, Bitman, and Harris, *Poultry Science* 1971: 50: 656-659

[113] The CDC writes, “Workers heavily exposed to DDT have not had more cancer than workers not exposed to DDT.”

As an autobiographical note, my first professional project as a newly minted programmer in the 70s was to write the software for a New Jersey state government study of cancer caused by industrial chemicals in the state, which “everyone knew” was a huge problem. The actual data remained stubbornly uncooperative, showing no significant correlations. Cancer rates in rural Canada were higher than NJ.

[114] Leiserowitz, A., Maibach, E., Roser-Renouf, C., Rosenthal, S., & Cutler, M. (2017). *Climate change in the American mind: May 2017*. Yale University and George Mason University. New Haven, CT: Yale Program on Climate Change Communication.

[115] D.J. Arendt, et al, n, 2014: *Key economic sectors and services*. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Working Group II, Chapter 10, IPCC AR5, p. 662

[116] David Wallace-Wells, *The Uninhabitable Earth*, New York Magazine, July 9, 2017

[117] U.S. Government Accountability Office [formerly known as the General Accounting Office] report GAO-17-720 Climate Change, available at https://www.energy.senate.gov/public/index.cfm?a=files.serve&File_id=90ECDE3F-38AF-47DB-8326-D38046D1E87E

[118] That is not to say that the science itself isn't biased and warped by the political priorities of the funding agencies. It is. But that is actually the most reassuring part of the business: even with literally billions of dollars of incentive to find the most alarming results possible, that when you get down to the bottom line the best they have managed to come up with is a 3% hit at the end of a century. There is no "crisis" here.

[119] <http://www.newyorker.com/tech/elements/roads-habitat-fragmentation>

[120] ... such as Japan's TechnoFarm, which produces more lettuce per year in a one acre building than 300 acres of outdoor farm:

<http://spread.co.jp/en/technofarm/>

[121] Do remember that the national 55-mph maximum speed limit was introduced by President Jimmy Carter specifically as an energy conservation measure.

[122] <http://www.abc.net.au/news/2017-06-27/sa-recycling-business-power-bills-rise-causing-closure/8654638>

[123]

http://en.wikipedia.org/wiki/Corporate_Average_Fuel_Economy#Standards_by_model_year.2C_1978-2011

[124] Bryan Burrough: *Days of Rage: America's Radical Underground, the FBI, and the Forgotten Age of Revolutionary Violence*, Penguin, 2016

[125] See, for example, J. B. Peires, *The Dead Will Arise: Nongqawuse and the Great Xhosa Cattle-Killing Movement of 1856-7*, Indiana University Press, 1989

[126] Nina Mazar, Chen-Bo Zhong, *Do Green Products Make Us Better People?* Psychological Science 21, Issue 4, March 5, 2010

[127] e.g. Michael P. Hall, Neil A. Lewis, Jr., Phoebe C. Ellsworth, *Believing in climate change, but not behaving sustainably: Evidence from a one-year longitudinal study*, Journal of Environmental Psychology V56, April 2018, Pp 55-62 <https://doi.org/10.1016/j.jenvp.2018.03.001> It's significant that the result keeps holding up because the overwhelmingly

left-wing social science community has a strong bias *against* the conclusion.

[128] Published in the August, September, and October 1930 issues of *Amazing*. At least one source claims that Smith was writing it as early as 1927. http://en.wikipedia.org/wiki/E._E._Smith, accessed 7/18/12

[129] <http://www.gutenberg.org/ebooks/20707>

[130] <http://parkitnyc.com/driving-nyc/nyc-bridge-tunnel/udson-river-bridges-tunnels/>

[131] 96 knots: <https://robinsonheli.com/r22-specifications/>

[132] D. S. L. Cardwell, *Turning Points in Western Technology*, (New York: SHP/Neale Watson, 1972), p. 198. Emphasis in the original.

[133] By 2000, modern plants produced 75 cars per worker per year, another almost but not quite factor of 4.

[134] Data from <http://www.fhwa.dot.gov/bridge/nbi/yrblt02.xls> [135] Tax

Foundation [136] cf. <http://www.economist.com/news/leaders/21647614-poor-land-use-worlds-greatest-cities-carries-huge-cost-space-and-city> [137]

Congestion is measured as the excess time taken on roads with existing traffic, compared to the time if each trip were made with no traffic. cf.

Randal O'Toole, *Gridlock: Why We're Stuck in Traffic and What to Do*

About It [138] Randall O'Toole, *The Vanishing Automobile and Other Urban Myths: How Smart Growth will Harm American Cities*; for a fuller

description of one particular case, Portland OR's "light-rail Mafia," see <http://www.cato.org/publications/policy-analysis/debunking-portland-city-doesnt-work>

[139] James A. Dunn, Jr., (Rutgers), *Driving Forces: The Automobile, Its Enemies, and the Politics of Mobility*, tables 4-3 and 4-4

[140] SF Weekly News, *The Muni Death Spiral*, Apr 14 2010

[141] In the real world, virtually all pilots use GPS, iPad, and other modern electronic devices. But you are required to learn to do it the old-fashioned way, just in case.

[142] <http://www.wwiifoundation.org/students/wwii-aircraft-facts/>

[143] Well, almost. The pressure on the top is actually 1.28 ounces less than that on the bottom. But by a strange coincidence, the air inside the box just happens to weigh 1.28 ounces, cancelling the unbalanced force. If you replaced it with helium, weighing only 0.18 ounces, you would get 1.1 ounces of lift.

[144] If you ever hear anyone arguing about Newton vs Bernoulli as a proper explanation of lift, please remember that as valid physics, both must be true at the same time. The pressure patterns of accelerating flows cause the momentum change in the airstream, or vice versa. The two descriptions are inseparable.

[145] Simulated with the SU2 open-source fluid dynamics program at Mach 0.2, and visualized with the open-source ParaView viewer.

[146] See Abbot & von Doenhoff, *Theory of Wing Sections*, pp 538-9.

[147] In 1931, Jim Ray took off from the White House lawn in a PCA-2 in a measured 44 feet.

[148] Andreas Schäfer, *Regularities in Travel Demand: An International Perspective*, J. Transportation and Statistics, Dec. 2000

[149] <http://pal-v.com/the-pal-v-one/specifications/>

[150] The batteries of the day were about 40 Wh/kg; commercially available LiPo cells today are about 185. Clarke wanted 4000, which would be satisfactory for automotive power; it represents roughly the same usable energy to weight as gasoline.

[151] <http://www.boeing.com/commercial/747family/specs.html> [152] Since I originally researched this chapter, oil and gas prices have dropped significantly; Jet-A is typically from \$4-5/gal at the moment, ranging from \$3.25 at Ocean City, MD to \$7.69 at Reagan/National. Even so it still costs hundreds of thousands to fuel the 747.

[153] <http://www.eia.gov/tools/faqs/faq.cfm?id=22&t=6>

[154] No, of course not exactly. You would have to use each fuel in perfectly even proportions for a simple average to hold. But the bottom line, that chemical fuels are in general about 1000 times as expensive as nuclear for the same energy, is true.

[155] A megawatt diesel generator burns about 80 gallons, 500 pounds, of fuel per hour. A megawatt wind turbine, by amusing coincidence, goes through about the same amount of lubricating oil per year. But a megawatt engine burning uranium would consume less than one pound of it in a year.

[156] A 1-foot cube battery could run the lights on your car, but not the car itself.

https://mipt.ru/english/news/prototype_nuclear_battery_packs_10_times_more_power [157]

https://en.wikipedia.org/wiki/2011_T%C5%8Dhoku_earthquake_and_tsu

nami#Damage_and_effects The heroic older workers who were allowed to enter the plant for emergency repairs with higher than normal dose limits are expected to have a 1% greater risk of cancer.

[158]

http://www.slate.com/articles/health_and_science/science/2013/09/fukushima_disaster_new_information_about_worst_case_scenarios.single.html
Of course, Fukushima was not all sweetness and light. There was radiation release, although in super slow motion compared to the tsunami and earthquake. The power plant was idiotically misdesigned, first by siting it on the shore in a known earthquake/tsunami area! The emergency core cooling generators were in a basement, first to get flooded in the event of a tsunami. Its operation was bureaucratically micromismanaged, and it will be enormously expensive to clean up.

[159] [http://dose-response.org/wp-content/uploads/2015/12/WSJ-](http://dose-response.org/wp-content/uploads/2015/12/WSJ-2015Dec2_A_nuclear_paradigm_shift-1.pdf)

2015Dec2_A_nuclear_paradigm_shift-1.pdf [160] James Conca, *How Deadly Is Your Kilowatt? We Rank The Killer Energy Sources*

<http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/>

[161] <https://www.theguardian.com/science/blog/2016/apr/11/time-dispel-myths-about-nuclear-power-chernobyl-fukushima> [162] cf Petr Beckmann, *The Health Hazards of Not Going Nuclear*, Golem Press, 1976

[163] Y2K p. 71

[164] Olivier Deschenes, Enrico Moretti, *Extreme Weather Events, Mortality and Migration*, NBER Working Paper No. 13227 July 2007.
<http://www.nber.org/papers/w13227>

[165] <http://www.cringely.com/2009/03/31/three-mile-island-memories/>

[166] or 4000 milliSieverts. The Gray and the Sievert are the same in the case of X-rays. Other types of radiation have a dose multiplier for Sieverts, a measure of physiological impact which varies with radiation type, compared to Grays, which is purely a measure of deposited energy. see Appendix D for a longer explanation of all the units.

[167] e.g. <http://news.mit.edu/2011/explained-radioactivity-0328>

[168] by J. A. Siegel *et al.*, The Birth of the Illegitimate Linear No-Threshold Model: An Invalid Paradigm for Estimating Risk Following Low-dose Radiation Exposure, in *Am. J. Clin. Oncol.* doi: 10.1097/COC.0000000000000244

[169] Tubiana, et al, The Linear No-Threshold Relationship Is Inconsistent with Radiation Biologic and Experimental Data, *Radiology*. 2009 Apr; 251(1): 13–22. <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2663584/>

[170] <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/bio-effects-radiation.html>

[171] And yes, it was almost entirely regulation: see J Lovering, A Yip, & T Nordhaus, *Historical construction costs of global nuclear power reactors*, *Energy Policy* 91, April 2016, pp 371-382, <https://doi.org/10.1016/j.enpol.2016.01.011>

[172] Nuclear Power Learning and Deployment Rates; Disruption and Global Benefits Forgone, *Energies* 2017, 10(12), 2169; doi:10.3390/en10122169

[173] Dec. 1, 2015, by Holman Jenkins, Jr., staff columnist [174] <http://nucleargreen.blogspot.com/2011/11/sherrell-greene-on-liquid-chloride.html>

[175] <http://www.postregister.com/articles/featured-news-daily-email-west/2017/01/14/nuscale-celebrates-last-minute-nuclear-milestone>

[176] <http://www.wsj.com/articles/obama-torpedoes-the-nuclear-navy-1432591747>

[177] http://www.climatechangebusiness.com/industry_segments

[178] In the 11 years after the Kyoto Protocols went into effect in 2005, atmospheric CO₂ per NOAA ESRL Mauna Loa observatory increased at 2.08 ppm/year. In the previous 11 years the rate had only been 1.80. Remember that energy per capita in the US had already flatlined in the 1970s. The Copenhagen Consensus Center, which does cost-benefit analyses of various kinds of investment in improving the world, finds that each dollar invested to reduce malnutrition, for example, produces \$59.00 worth of benefit, while each dollar spent to prevent climate change produces \$0.02 worth of benefit.

[179] Ansgar Belke, Christian Dreger, Frauke de Haan: *Energy Consumption and Economic Growth: New Insights into the Cointegration Relationship*, Deutsches Institut für Wirtschaftsforschung Discussion Paper 1017, http://www.diw.de/documents/publikationen/73/diw_01.c.357400.de/dp1017.pdf

[180] David C. Rode, et al, The retirement cliff: Power plant lives and their policy implications *Energy Policy* V106, July 2017, pp 222-232. <https://doi.org/10.1016/j.enpol.2017.03.058>

[181] Kenneth S. Krane, *Introductory Nuclear Physics*, Wiley, 1988. This is a rewrite and update of the even more classic Halliday text of the same title from 1955.

[182] If this were precisely true, the two peaks in the graph would be mirror images of each other. There is a “spray” of neutrons—the ones that propagate the chain reaction—and very light nuclei which changes the output by about 2%. see <http://ie.lbl.gov/fission/235ut.txt> [183]

The current best physics for this, as far as I know, is a semi-empirical mashup of the two theories called the “finite-range liquid drop model with shell corrections.” see, e.g., Möller, Madland, Sierk & Iwamoto, “Nuclear fission modes and fragment mass asymmetries in a five-dimensional deformation space” *Nature*, v409, p785 (2001) [184]

Bulgac et al, *Induced Fission of ^{240}Pu within a Real-Time Microscopic Framework*, arXiv:1511.00738v2

[185] <http://www.physicscentral.com/buzz/blog/index.cfm?postid=157878300426073350>

[186] <http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0901>

[187] <http://www.britannica.com/EBchecked/topic/421763/nuclear-reactor/302452/History-of-reactor-development> [188]
http://en.wikipedia.org/wiki/IBM_1401

[189] *V-22 Osprey Hydraulic System*

<http://www.dtic.mil/dtic/tr/fulltext/u2/a403472.pdf> [190]

<http://www.moller.com/index.php?>

[option=com_content&view=article&id=50&Itemid=58](http://www.moller.com/index.php?option=com_content&view=article&id=50&Itemid=58), accessed 10 Oct 2011

[191] see Barnes W. McCormick, Jr: *Aerodynamics of V/STOL Flight* for the semi-empirical formula.

[192] Wing loading on a Beechcraft Bonanza (prop) is about 25 pounds per square foot, on a Cessna Citation (jet) about 40. (A Boeing 747 has a wing loading of 150.) A Prius has a curb weight of about 3000 lbs + 800 lbs passengers and cargo, and a ground footprint of 5.5x14.5 feet. Plenty of room for (stacked) wings; the only major engineering challenge is an extending mechanism.

[193] [http://www.aopa.org/News-and-Video/All-](http://www.aopa.org/News-and-Video/All-News/2015/January/20/AOPA-supports-LSA-status-for-road-worthy-airplane)

[News/2015/January/20/AOPA-supports-LSA-status-for-road-worthy-airplane](http://www.aopa.org/News-and-Video/All-News/2015/January/20/AOPA-supports-LSA-status-for-road-worthy-airplane) [194]

https://www.foresight.org/roadmaps/Nanotech_Roadmap_2007_main.pdf

[195] <http://www.islandone.org/MMSG/9612.html> [196] Advanced Automation for Space Missions, held at University of Santa Clara, NASA CP2255

[197] Full text available online:

<http://www.molecularassembler.com/KSRM.htm> [198] Hall, J:

“Architectural Considerations for Self-replicating Manufacturing Systems,” *Nanotechnology* 10, 1999, p323. doi:10.1088/0957-4484/10/3/316

[199] <http://secretsoftheice.com/funn/2016/06/28/reconstruction/>

[200] Pierre de Latil, *Thinking by Machine* [201] See Conway and Siegelman’s monumental biography of Norbert Wiener, *Dark Hero of the Information Age*, or Chapter 3 of my *Beyond AI*. Briefly, Wiener’s wife hated McCulloch and fabricated stories about his seducing the Wieners’ daughter.

[202] plus or minus 8 billion: Azevedo FA1, Carvalho LR, Grinberg LT, Farfel JM, Ferretti RE, Leite RE, Jacob Filho W, Lent R, Herculano-Houzel S. “Equal numbers of neuronal and nonneuronal cells make the human brain an isometrically scaled-up primate brain.” *J Comp Neurol.* 2009 Apr 10;513(5):532-41. doi: 10.1002/cne.21974.

<http://www.ncbi.nlm.nih.gov/pubmed/19226510>

[203] <http://awards.acm.org/images/awards/140/articles/4622167.pdf> [204]

<http://www.britannica.com/science/Little-Ice-Age> [205] e.g. Lyndal Roper: *Witch Craze: Terror and Fantasy in Baroque Germany* [206]

http://en.wikipedia.org/wiki/Simon-Ehrlich_wager accessed 2009

[207] <http://www.nytimes.com/2015/06/01/us/the-unrealized-horrors-of-population-explosion.html> [208]

<http://climatecommunication.yale.edu/publications/climate-change-american-mind-may-2017/>

[209] Hsiang et al, “Estimating economic damage from climate change in the United States,” *Science* 30 Jun 2017: Vol. 356, Issue 6345, pp. 1362-1369 DOI: 10.1126/science.aal4369

[210] Mike Gray, *Angle of Attack: Harrison Storms and the Race to the Moon*, Penguin 1994. It is, of course, a reference to the sign over the gate at the rocket construction site in *When Worlds Collide*.

[211] <http://www.schuebeler-jets.de/en/products/hst-en.html> Note that the compact form costs you in efficiency; a modern electric motor driving a 32-inch prop can get 15 pounds of thrust per kW instead of 3.6.

[212] This would be less than a third the actual energy in the avgas, but the electric motors use it more efficiently.

[213] <http://web.mit.edu/newsoffice/2013/ionic-thrusters-0403.html> [214]

Using the open-source SU2 (Stanford University Unstructured mesh) computational fluid dynamics codes. see <http://adl.stanford.edu/>

[215]

Fifties SF writers, Heinlein and Piper at least, foresaw RATO being used for flying cars. RATO (rocket assisted takeoff) was developed by the German military in WWII and the US thereafter, to the point of complete workability. You could take off in a regular airplane from the back of a truck, with no runway whatsoever. It was noisy as hell, of course, but I am at a loss to understand why it was then essentially abandoned. The military has since spent many billions on VTOL aircraft.

Parachutes, rockets, or whatever, an emergency landing system would only have to provide about 2 gees backward thrust for two seconds to bring a car from its 100-knot lifting-body glide speed to something survivable on the ground.

[216] Googling for “open source autopilot” returns five projects on just the first page: Paparazzi, ArduPilot, Autopilot, Flying Fox, and OpenPilot.

(accessed 11 Oct 2011) [217] <http://www.artba.org/government-affairs/policy-statements/highways-policy/>

[218] Sept. 26, 2014

[219] see an introductory analysis at

<http://www.ce.jhu.edu/perspectives/studies/>

Eiffel%20Tower%20Files/ET_Introduction.htm [220]

titanium.[http://www.economist.com/news/science-and-](http://www.economist.com/news/science-and-technology/21642107-alloy-iron-and-aluminium-good-titanium-tenth)

technology/21642107-alloy-iron-and-aluminium-good-titanium-tenth [221]

Airlords of Han; see also *Armageddon: 2419 A.D.*

[222] <http://news.nationalpost.com/news/russias-rich-hiring-luxurious-ambulance-taxis-to-beat-moscows-traffic-jams> [223]

<http://www.bloombergview.com/articles/2015-06-01/real-new-yorkers-can-say-goodbye-to-all-that> [224] Remember how air travel had a rate of 0.05 deaths per billion km and driving 3.1? The corresponding figure for walking is 54.2.

[225] <http://business.financialpost.com/fp-comment/i-knew-jane-jacobs-and-everything-urban-lefties-say-about-her-is-wrong> [226] Asimov, *The*

Caves of Steel; Clarke, *Against the Fall of Night*; Heinlein, *The Roads Must Roll* [227] <http://www.telegraph.co.uk/science/2016/04/14/move-to-a-leafy-suburb-to-cut-cancer-risk/>

[228] e.g. Kolodny & Kaplan, Uranium isotopes in sea-floor phosphorites, *Geochimica et Cosmochimica Acta* 34, 1, Jan. 1970, pp 3-24

[229] see, e.g., An, Qian; Gordon, Peter; Moore, James E.. A note on commuting times and city size: Testing variances as well as means. *Journal of Transport and Land Use*, [S.l.], v. 7, n. 2, p. 105-110, jul. 2014.

[230] <http://www.visual-memory.co.uk/amk/doc/0075.html> [231] The specific impulse of a fuel is the number of seconds a given amount of the fuel can produce a force equal to its (initial) weight.

[232]

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050160960_2005161052.pdf [233] Add a neutron and you get a combined alpha and beta decay. This is not a chain reaction, because it does not produce a new neutron.

[234] There is a newly-discovered low-energy trajectory, called the ballistic capture transfer, which takes about as long but avoids the launch window restriction. arXiv:1410.8856 [astro-ph.EP]

[235] The Davy Crockett hand-launched nuclear bazooka is generally thought of as the smallest, but Taylor claimed later that an entire implosion weapon that would fit into a 6-inch ball had been built. The S.O.B, or Super Oralloy Bomb, was our biggest non-hydrogen bomb; it had a yield of half a megaton. (Oralloy is “Oak Ridge alloy,” i.e. highly enriched U-235.) [236] *E.g.* the Celebrity Reflection [237] George Dyson, Project Orion: the true story of the atomic spaceship, p.230. READ THIS BOOK.

[238] ...assuming the average person had 40 years to live, using US cancer incidence rates. [https://www.cancer.gov/about-](https://www.cancer.gov/about-cancer/understanding/statistics)

[cancer/understanding/statistics](https://www.cancer.gov/about-cancer/understanding/statistics) [239] The trilogy won a Hugo Award for “Best All-Time Science Fiction Series” in 1966. Presumably the SF fans used a time machine to make sure.

[240] M. Law and S. Kim, *The rise of the American regulatory state*, chapter 8 in Handbook on the *Politics of Regulation*, ed. David Levi-Faur

[241] Ray J. Solomonoff, *The time scale of artificial intelligence: Reflections on social effects*, Human Systems Management v5 pp149-153, 1985. Von Neumann and Good had earlier advanced informal models, and Asimov predicted “an Intellectual Revolution” by analogy to the Industrial

Revolution. See also J Storrs Hall, *Further Reflections on the Timescale of AI*, at the Solomonoff memorial conference (and from which this section was adapted).

[242] The semiconductor industry in other regions, notably Asia/Pacific, has expanded considerably over the period.

[243] US Bureau of the Census, Economic census numbers for semiconductor manufacturing sector (NIACS code 334413), economic census for 1992, 1997, 2002, and 2007. *cf.*

http://factfinder.census.gov/home/saff/main.html?_lang=en. After correcting for correlation with the overall US economy, a null hypothesis of the steady state described cannot be rejected at a 95% confidence level.

[244] The equation for the quadratic fit is $f(t) = 0.000723t^2 - 2.69t + 2496$, i.e. ops/sec/\$1000 is predicted to be $Q(t) = 10^{f(t)}$ for t the year number. (Figures before 2000 from Kurzweil 2005, figures from 2004 and 2011 from machines constructed by the author.) This is the form of the integral of the product of a linear term and an exponential, which suggests a model with a linear network effect as well as capital re-investment.

[245] Stable enough with a 900-year halflife, it has a thermal neutron capture cross section of 5000 barns (vs, *e.g.*, 585 for U-235). Note that is only the moderated reaction: *Popular Science* in 1961 told us that Californium could be used to make bullet-sized atom bombs, but the unmoderated (fast-neutron) critical mass of Cf is more like 11 pounds.

[246] And no, you couldn't extract the plutonium to make a bomb; the smallest steel-reflected non-moderated (i.e. the bomb reaction) critical mass of Pu-241 is over 11 pounds.

<https://www.euronuclear.org/info/encyclopedia/criticalmass.htm> [247] Its half-life of 138 days is something of a "sweet spot," making it last long enough to use but have a high enough level of radioactivity to be very toxic. It emits high-energy, 5.3 MeV, alphas; for comparison the betas emitted by tritium are 0.018 MeV.

[248]

Observation of Bound-State β – Decay of Fully Ionized ^{187}Re : $^{187}\text{Re} - ^{187}\text{Os}$ Cosmochronometry

F. Bosch, et al, Phys. Rev. Lett. 77, 5190 – 23 December 1996

[249] <http://www.cbsnews.com/video/watch/?id=4955212n/>

[250] Defense Analysis Report DIA-08-0911-003, 13 November 2009, see <http://lenr-canr.org/acrobat/BarnhartBtechnology.pdf> [251] “Cold Fusion: the Scientific Fiasco of the Century”

[252] Widom, Allan, Larsen, Lewis, "Ultra Low Momentum Neutron Catalyzed Nuclear Reactions on Metallic Hydride Surfaces," European Physical Journal C - Particles and Fields, Vol. 46(1), p.107-110 (2006) Electron capture is also the preferred theory of the people at Brillouin Energy, who by some accounts are capable of excess heat production in their apparatus 100% of the time.

[253] Or, if you want to get deeper into the structure, pushes the positively charged Up quarks one way, and pulls the negatively charged Down quarks the other. But *nobody* has ever done a simulation of even a milligram of loaded palladium in quantum electrodynamics without using the Born-Oppenheimer approximation, in which the nuclei are treated classically, much less a quantum chromodynamic one.

[254] #5,928,483, “Electrochemical Cell Having a Beryllium Compound Coated Electrode” and US #8,419,919, “System and Method for Generating Particles”.

[255] Hora, H., Eliezer, S., Kirchhoff, G., Nissim, N., Wang, J., Lalousis, P., . . . Kirchhoff, J. (2017). Road map to clean energy using laser beam ignition of boron-hydrogen fusion. *Laser and Particle Beams*, 35(4), 730-740. doi:10.1017/S0263034617000799

[256] <https://www.technologyreview.com/s/601045/this-factory-robot-learns-a-new-job-overnight/>

[257] see <http://karpathy.github.io/2015/05/21/rnn-effectiveness/>

[258] cf. Silver et al, *Nature* 529, 484–489 (28 January 2016) doi:10.1038/nature16961.

[259] Sam Adams, Itmar Arel, Joscha Bach, Robert Coop, Rod Furlan, Ben Goertzel, J. Storrs Hall, Alexei Samsonovich, Matthias Scheutz, Matthew Schlesinger, Stuart C. Shapiro, John Sowa: *Mapping the Landscape of Human-Level Artificial General Intelligence*, AI magazine V33#1, 2012; DOI: <http://dx.doi.org/10.1609/aimag.v33i1.2322> <http://www.aaai.org/ojs/index.php/aimagazine/article/view/2322> My contribution was, you guessed it, the Wozniak test.

[260] You can cut these numbers roughly in half if you use either a statistical model or a game playing engine for probabilistic compression,

but that would imply you already knew something about strategy. Here we are concerned with how simple the rules make the game for a program attempting to learn strategy from scratch. Note that Deepmind followed up AlphaGo with AlphaZero, a program which did just that.

[261] <http://www.bloomberg.com/news/articles/2016-03-18/why-google-wants-to-sell-its-robots-reality-is-hard> [262] BLS data; thanks to Mark Perry for the pointer [263] it's $45373e^{0.0114t + 0.0001116t^2}$ where t is year-1950.

[264] An antarctic cod more commonly advertised as “Chilean sea bass.”

[265]

http://midwest.chicagofedblogs.org/archives/2010/08/bill_strauss_mf.html

[266] And when I say “we”, I mean robot computer scientists, all of whom will have read all my books.

[267] <http://www.statisticbrain.com/employee-theft-statistics/>

[268] White, March, Lawrence, Vera, Sylvester, Brady, and Bailey:

“Measurement of Propulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum”, *AIAA Journal of Propulsion and Power*, December 2016

[269] Martin Tajmar, Matthias Kößling, Marcel Weikert, Maxime Monette: *The SpaceDrive Project - First Results on EMDrive and Mach-Effect Thrusters*, Space Propulsion Conference, Seville, Spain, May 2018

[270] Tajmar, Martin. (2017). Mach-Effect thruster model. *Acta Astronautica*. 141. 8-16. 10.1016/j.actaastro.2017.09.021.

[271] Note that since I originally gave a talk about space piers at the International Space Development Conference in 2005, further technical work has been done on the concept.

[272] NASA launch costs. SpaceX CEO Elon Musk has stated that he believes his company can achieve launch costs in the \$1000/kg range with reusable boosters.

[273] In fact, they have been tested at orbital speeds (in a vacuum chamber fed by a particle accelerator!) by the European Space Agency:

http://www.esa.int/Our_Activities/Space_Engineering_Technology/World-first_firing_of_air-breathing_electric_thruster [274] 5 times with 2% growth over the century, 10 times with 3% growth.

[275] Just about right for owning private spaceships, for example.

[276] To be precise, according to IPCC AR5, the CO_2 we've added to the atmosphere since 1750 has caused an extra $1.65 \pm 0.35 W/m^2$.

[https://www.ipcc.ch/pdf/assessment-report/ar5/syr/](https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf)

AR5_SYR_FINAL_All_Topics.pdf [277] Actually it ranges from 300 over the tropics to 200 over the Great White North.

[278] In simplistic classical physics. In reality, trying to put that much energy into that little space would do things that would make the Large Hadron Collider look like a lightning bug.

[279] CRISPR stands for “clustered regularly interspaced short palindromic repeats,” which are a major feature of the DNA sequences associated with a powerful anti-viral defense mechanism found in bacteria and prokaryotic archaea. The DNA-editing capabilities of this mechanism have been adapted into a broadly applicable tool.

[280] see Appendix F

[281] [http://www.ecfr.gov/cgi-bin/text-idx?](http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title49/49tab_02.tpl)

[tpl=/ecfrbrowse/Title49/49tab_02.tpl](http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title49/49tab_02.tpl) [282] Bertrand R. Jordan, *The Hiroshima/Nagasaki Survivor Studies: Discrepancies Between Results and General Perception*, GENETICS August 1, 2016 vol. 203 no. 4 1505-1512; DOI: 10.1534/genetics.116.191759

[283] BEIR V, BEIR VII [284] Lindqvist et al, *Avoidance of sun exposure as a risk factor for major causes of death: a competing risk analysis of the Melanoma in Southern Sweden cohort*. Journal of Internal Medicine, 2016; DOI: 10.1111/joim.12496

[285] Lucas, RM and Ponsonby, AL: Ultraviolet radiation and health: friend and foe. *MJA (Medical Journal of Australia)* 177:594-598; Lucas, McMichael, Smith, & Armstrong, *Solar Ultraviolet Radiation*, World Health Organization Environmental Burden of Disease Series, No. 13

http://www.who.int/uv/health/solaruvradfull_180706.pdf [286] EJ Calabrese and LA Baldwin, *The Hormetic Dose-Response Model Is More Common than the Threshold Model in Toxicology*, Toxicol. Sci. (2003) 71 (2): 246-250. doi: 10.1093/toxsci/71.2.246